Impacts of tephra fall on buildings from the 2017-2018 eruption of Manaro Voui volcano, Ambae Island, Vanuatu

A thesis

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Frontispiece

Buildings constructed using traditional materials and design in Sakao village, South Ambae, Vanuatu, that were damaged from the July 2018 tephra fall from Manaro Voui volcano (photo credit Carol Stewart).

Abstract

Building damage from thick tephra fall can have a substantial impact on exposed communities close to erupting volcanoes. However, historical records of the impact of thick tephra fall on buildings are limited. Moreover in the tropical, southwest Pacific there are few documented accounts of the impacts of multi-phase and basaltic tephra falls to traditional thatch buildings. In 2017/18 a multi-phase, explosive eruption from Manaro Voui volcano, Ambae Island, Vanuatu damaged local buildings. This thesis presents a comprehensive record of the impact of the March/April and July 2018 tephra falls from Manaro Voui to address current gaps in the literature regarding traditional building damage from tephra fall.

Impacts of tephra fall on buildings on Ambae island were recorded during two field visits in April and August 2018. Field and photographic surveys were used to record damage to 589 buildings from the March/April and July 2018 tephra falls from Manaro Voui. The construction characteristics of each building were described from observations in the field.

The damage buildings sustained from tephra fall was described according to a ‘damage state’ framework, customised for this study. Complete collapse of traditional buildings was observed from ~40 mm of tephra deposition. However, some traditional buildings sustained no damage in areas with 200 mm of tephra deposition. The variation in building damage, even at similar tephra loadings, appears to have been influenced by a wide range of pre-eruption building conditions, including the age of materials and termite damage to wooden structural members or the application of diverse mitigation methods.

Several rapidly implemented mitigation methods were observed that reduced building damage and maintained building habitability in areas exposed to tephra fall. The most effective method for minimising building damage appeared to be the installation of tarpaulins on thatch roofs, which aided tephra shedding thereby reducing loading. Preventing tephra ingress in buildings (to maintain adequate habitability) was challenging due to the highly-ventilated nature of buildings in tropical

climates, exacerbated by the frequent ash falls and remobilisation of tephra by passing vehicles, people and wind.

This study presents the first empirical dataset for traditional Pacific Island buildings damaged by tephra fall. These results contribute towards the otherwise limited global empirical data available for tephra fall building damage, improving the current evidence base in forecasting future volcanic impacts.

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Table of Contents

LIST OF FIGURES

LIST OF TABLES

Chapter one: Introduction

1.1 Context of study

Due to global population growth, exposure to volcanic hazards is increasing. An estimated >800 million people are now living within 100 km of a volcano that has erupted in the past 12,000 years (Brown, 2015; Chester et al. 2001; Doocy et al. 2013; Freire et al. 2019). This increasing exposure drives the need for understanding the likely impacts of volcanic hazards on society so as to inform effective risk management.

A key aspect of society is the built environment, which can be defined as a human-made space where people live and work and includes the buildings and spaces created or modified by them (Roof & Oleru, 2008). Understanding volcanic hazard impacts to the built environment has been a focus of volcanic disaster risk researchers for the past 40 years (Blong 1984; Spence et al. 2005; Jenkins et al 2014; 2015; Wilson et al. 2014). Of the multiple hazards a volcano can produce, tephra fall is the most widespread. Therefore, understanding its impacts on the built environment has been a key research focus (Jenkins et al. 2015). Tephra; fragments of rock explosively ejected from a volcano, consists of a range of particle sizes (ash (< 2 mm), lapilli (2-64 mm) and blocks and bombs (> 64 mm)). Tephra of all particle sizes can threaten human health and damage buildings, infrastructure, and agriculture (e.g. Spence et al. 1996; Blong, 2003; Leonard et al. 2005; Hansell et al. 2006; Horwell, 2007; Wilson et al. 2007, 2011a, 2011b, 2012; Cronin et al. 1997; Blake et al. 2015; Craig et al. 2016a, 2016b; Hayes et al. 2019). While tephra fall deposits in excess of 100 mm are usually necessary to produce tephra loads sufficient to cause damage to a building's structure, even thin tephra fall deposits can cause damage to non-structural building elements (e.g. gutters) or contaminate building interiors (Blong, 1996, 2003; Hayes et al. 2019). Understanding the likely impacts of volcanic hazards to the built environment is an essential part of Disaster Risk Reduction (DRR) which aims to prevent new and reduce existing risks (UNDRR, 2017). However, DRR must be informed by Disaster Risk Assessments (DRA) which determine the nature and extent of a disaster risk (UNDRR, 2017).

Risk assessments must be based on a robust understanding of the hazard and vulnerabilities of the elements exposed to that hazard (Blong, 1996). Current understanding of tephra fall hazard and its dispersion processes (e.g. Bonadonna 2006; Costa et al. 2006; Jenkins et al. 2012) is well advanced when compared to the vulnerability of buildings to tephra fall (Wilson et al. 2014). Building vulnerability models from tephra fall have mainly focused on the vulnerability of timber and masonry engineered buildings (e.g. Blong et al. (2017), Jenkins et al. (2014), Maqsood et al. (2014), and Spence et al. (2005)). Current gaps in our understanding of building vulnerability to tephra fall include the vulnerability of traditional thatch buildings (made from bamboo and palm tree-like materials) and non-damage related impacts on buildings such as disruption to habitability or functionality.

The isolation and remoteness of some rural areas means that traditional thatch buildings are a necessity as the expense and logistics of transporting non-traditional building materials can be a challenge. But despite prevalence and importance of traditional thatch buildings too many rural areas and/or less economically developed subsistence communities in Pacific Island nations, empirical post-eruption impact data for traditional thatch buildings (hereafter referred to as traditional buildings) is limited. Therefore, quantifying the vulnerability of traditional buildings exposed to tephra fall is challenging and assessing the associated risk difficult. Quantification of traditional building vulnerability to tephra fall is important for the preservation of life but it is also important to consider how tephra fall can negatively affect building habitability and resident livelihood. Understanding traditional building vulnerability to tephra fall is particularly important for Pacific Island nations as their small island landmasses and limited infrastructure and resources can make rapid evacuation or relocation particularly challenging (Shultz et al. 2016).

The 2017/18 eruption period of Manaro Voui volcano, Ambae Island, Vanuatu (Figure 1.1) provided an opportunity to record empirical data on tephra fall damage to traditional buildings. This study used an impact assessment to record the impact of the March/April 2018 and July 2018 tephra falls of Manaro Voui on buildings. Traditional buildings represent approximately 51% of residential buildings on Ambae (VNSO, 2016). Therefore, this thesis provides the first qualitative tephra fall impact assessment for traditional buildings. This thesis contributes to the currently limited number of studies that have recorded building impacts due to tephra fall (Spence et al. 1996; Blong, 2003; Hayes et al. 2019).

Because the 2017/18 eruption period of Manaro Voui was prolonged there was also an opportunity to record the evolution of building impacts. Two field visits to Ambae during April and August 2018 offered insights into how a prolonged, multi-phase eruption can exacerbate impacts; a key, but often under-appreciated, consideration represented in literature (Maqsood et al. 2014).

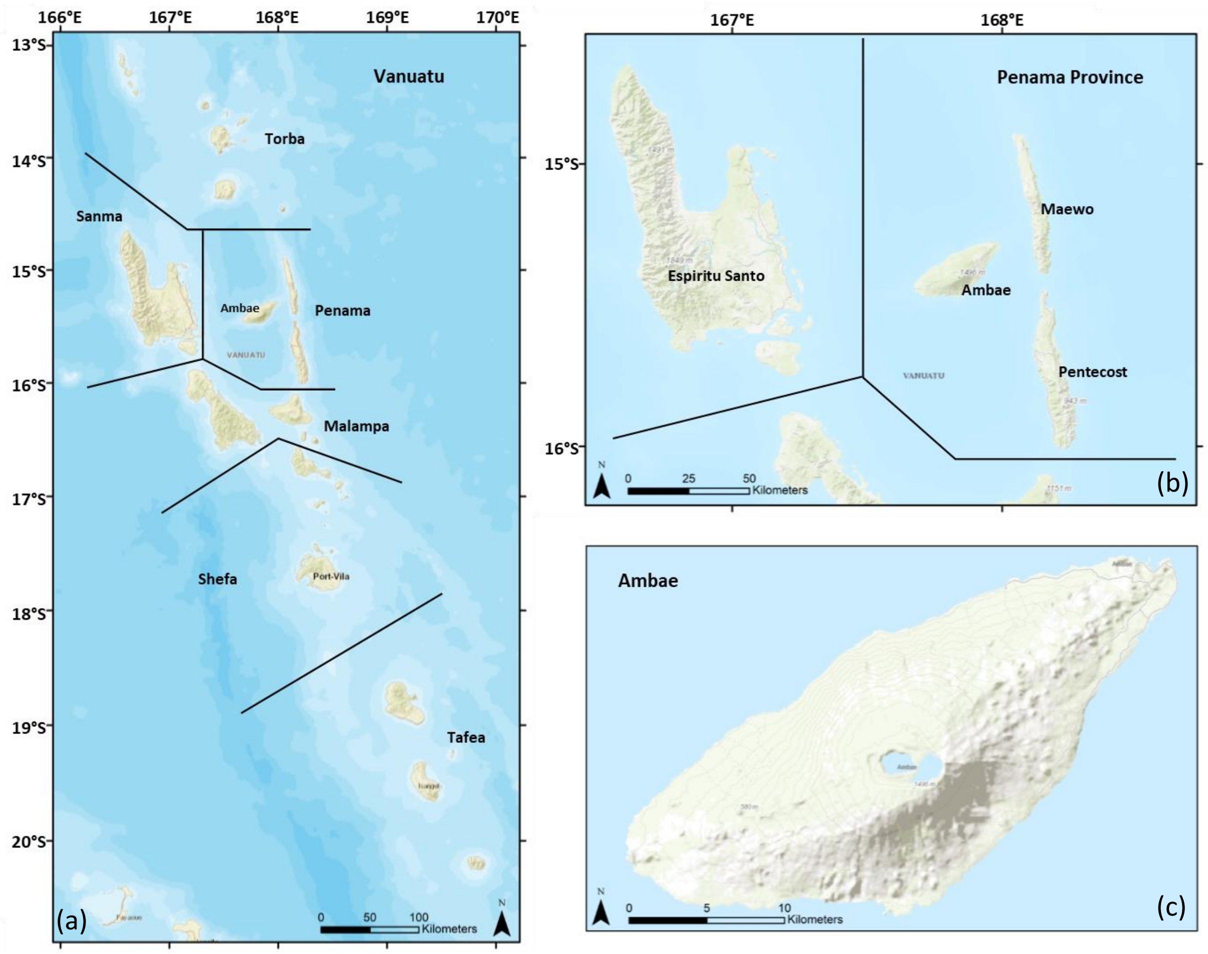

Figure 1.1 Location of Ambae island, Vanuatu. (a) Vanuatu archipelago and its six provinces, (b) Ambae, Maewo and Pentecost islands, (c) Ambae island.

1.2 CONCEPTUAL FRAMEWORK FOR DISASTER RISK REDUCTION

Section 1.4 outlines the global framework for Disaster Risk Reduction (DRR) presented in the Sendai Framework for Disaster Risk Reduction 2015-2030 (United Nations, 2015), the conceptual framework of this thesis. The scientific approach for volcanic risk assessments is presented to provide the structure used to meet the aims and objectives of this thesis (Section 1.2). Finally, an overview on Small Island Developing States (SIDS) is provided to highlight the challenges and opportunities of DRR in SIDS, which Vanuatu and therefore Ambae, is classified as being.

1.4.1 What is Disaster Risk Reduction?

In society, and particularly the media, disasters are often described as 'natural', implying that disasters are caused by, or at the fault of nature (O'Keefe et al. 1976; Kelman, 2010). However, it is argued that disasters are not natural and are in fact social constructions (Kelman, 2010). It is people who have decided to live, work and visit in areas where hazardous phenomena occur. If people were not there and a hazardous phenomenon occurs, there would be no disaster as there is no impact to people or society.

As disasters were becoming larger, more frequent, and increasingly unsustainable, society's focus on emergency response was incapable of alleviating the impacts disasters cause (PreventionWeb, 2015). As a result, rather than managing disasters after they have happened to reduce the overall losses of the disaster, disaster risk reduction focuses on managing the risk. Managing the risk considers the hazard and exposed assets and their inherent vulnerabilities and how the risk can be reduced before a potential disaster happens.

Disaster Risk Reduction (DRR) is the concept and practice of using systematic efforts to analyse and reduce disaster risks (UNDRR, 2019). Using DRR to analyse and understand a particular risk provides the foundation essential for informing decisions for managing that risk (GFDRR, 2014). Examples of using DRR to reduce risks include reducing the exposure of assets to hazards and reducing the vulnerability of people and property. DRR is achieved through Disaster Risk Management (DRM) which are the actions taken to prevent new risks, reduce existing risks and manage residual risk (UNDRR, 2015; UNDRR, 2017). Examples of DRM include land-use management, hazard monitoring, installing early warning systems, risk education and improving preparedness.

To aid the improvement of DRR globally, the Sendai Framework for Disaster Risk Reduction 2015-2030 was developed as an instrument to help manage disaster risk (UNISDR, 2015). The Sendai Framework is coordinated by the United Nations Office for Disaster Risk Reduction (UNISDR), who also monitor the progress of contributing Member States reducing their disaster risk. This thesis will contribute towards priority one of the Sendai Framework for Disaster Risk Reduction 2015-2030 'understanding risk' Priority one involves understanding the dimensions of disaster risk including the vulnerability and capacity of exposed assets, hazard characteristics and the local environment (United Nations, 2015). A brief overview of the Sendai Framework for Disaster Risk Reduction 2015-2030 is provided in Appendix A.

1.4.3 Scientific approach to volcanic risk assessment

The seminal work of Blong (2000) recommends that the consequences of volcanic eruptions should be viewed through a risk management framework. Risk management frameworks provide a systematic approach to conducting risk assessments by establishing the risk context and identifying and analysing the risk. Disaster risk assessments are only a single step in risk management frameworks. Basic risk management frameworks establish the risk context, conduct a risk assessment and provide risk treatment options all whilst maintaining communication with stakeholders and monitoring and reviewing the framework. An example of a risk management process is the AS/NZ:ISO 31000 (Figure 1.2). The results of a disaster risk assessment within a risk management framework are what are used to inform DRR decisions.

1.4.3.1 Establishing the context (Risk context)

Establishing the context involves identifying and understanding the internal and external parameters that need to be taken into consideration when assessing and managing a risk (AS/NZS, 2009). The risk context can include the social, cultural, political, financial, natural, economical and legal environment as well as the risk perception, relationships, roles, responsibilities and structure of stakeholders (AS/NZS, 2009). In this thesis the risk context is identified and provided in the literature review in Chapter Two.

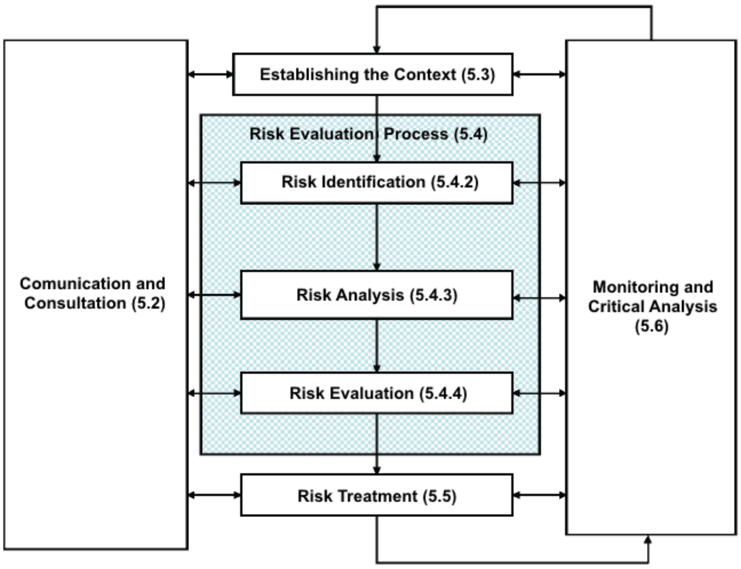

Figure 1.2 AS/NZS ISO 31000:2009 Framework for Risk Management. Retrieved from AS/NZS (2009).

1.4.3.2 Risk assessment

For the purpose of a risk assessment, risk is defined by UNISDR as "*the combination of the probability of an event and its negative consequences*" (UNISDR, 2009). This definition of risk is commonly expressed as the equation;

$$Risk = Probability \times (Hazard \times Exposure \times Vulnerability)$$

Before a risk can be identified, analysed and treated a comprehensive understanding of the risk in terms of the hazard, exposed assets and their vulnerabilities to the hazard must first be developed. Impact assessments are a process where the expected impact a hazard may have on an exposed asset can be estimated and evaluated. Impact assessments are achieved by combining a hazard footprint with exposed assets, and using the vulnerability of the exposed assets to identify the likely impact (Figure 1.3). When a hazard has already impacted an exposed asset the impact assessment process can be reversed. Using the observable impact to an asset that was exposed to a known or inferred hazard intensity, an understanding of the asset's vulnerability can be developed. UNISDR's definition of each constituent of an impact assessment is presented in Appendix A.

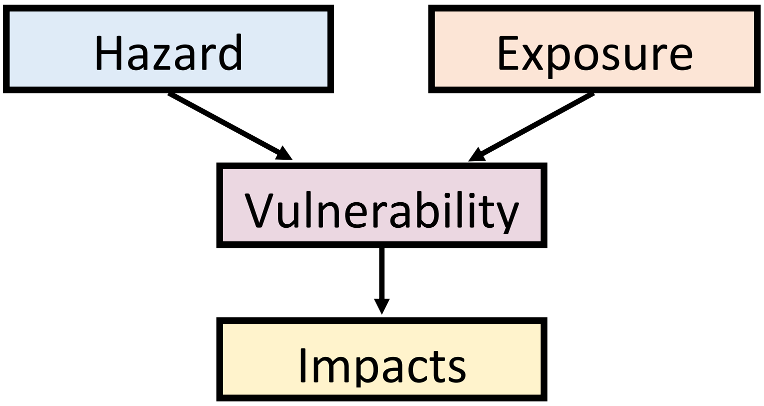

Figure 1.3 Conceptual model of the impact assessment process used as the framework for this thesis.

1.4.3.3 Risk treatment

Once a risk assessment is completed, risk treatment strategies are evaluated and may be implemented into a society if the risk assessment identifies that the assessed risk is unacceptable. The objective of this thesis is to use an impact assessment to record the impact tephra fall had on buildings on Ambae, rather than a risk assessment to quantify the risk. Therefore, risk treatment options are not presented and evaluated in this thesis, instead recommendations are made based on some of the results of this thesis which do identify some potential risk treatment options for reducing tephra fall impacts.

1.4.4 Small Island Developing States

The Sendai Framework recognises 52 Small Island Developing States (SIDS) of which Vanuatu is classified as one (Kelman & West, 2009; Shultz et al. 2016). SIDS face specific challenges which often warrant higher or unique vulnerabilities and risks that exceed the country's capacity to respond and recover from disasters or attain sustainable development goals (Mercer et al. 2007; United Nations, 2015; Shultz et al. 2016). These challenges are related to the country's size, geographic location and isolation, as well as elevated risks and exposure to the likes of sea level rise, climate change, and other natural and anthropogenic disasters (Kelman, 2006; Shultz et al. 2016). Despite these challenges, SIDS also have unique characteristics providing them with strong coping mechanisms such as traditional knowledge, small scale economies, a strong sense of community and tight kinship networks (Kelman, 2006). Because of these advantageous characteristics of SIDS, Mercer et al (2007), along with most DRR scholars and practitioners, emphasise that local residents of SIDS should be involved in the development of any DRR strategies. This can be achieved through a collaborative and interdisciplinary manner so that both the benefits of science and traditional knowledge are utilised. Cronin et al. (2004) is emphasised as an example where a participatory rural appraisal approach was adopted on Ambae to rebuild the respect and trust between the local and scientific community. By doing so Cronin et al. (2004) gained an understanding of the local risk context and perspectives to develop volcanic hazard management guidelines in collaboration with the local community and incorporate their viewpoints and perspectives into the results. Including the local community in this process resulted in an improvement in their overall awareness of volcanic risk.

As well as having a focus on DRR, the Sendai Framework encourages the implementation of the SIDS Accelerated Modalities of Action (SAMOA) Pathway, a framework aimed at helping SIDS reach their goals of sustainable development and DRR (United Nations, 2014). The SAMOA Pathway recognises that disasters disproportionately affect SIDS (United Nations, 2014), and therefore can hinder their sustainable development. There is therefore a need to reduce vulnerability, build resilience, increase preparedness both to respond and recover from disasters, raise awareness and strengthen monitoring and prevention (United Nations, 2014). In order to be successful in achieving sustainable development goals and reducing disaster risk, there is a need for international collaboration and strong partnerships for SIDS to overcome some of their challenges (United Nations, 2014, 2015). For this reason, the importance of the international collaboration between Vanuatu's Meteorological and Geohazards Department (VMGD) and New Zealand scientists that occurred as a part of this thesis, and other ongoing research occurring on the 2017/18 eruption period of Manaro Voui, is recognised as crucial for the further development of DRR in Vanuatu.

1.3 THESIS AIMS AND OBJECTIVES

The overall aims of this thesis are to use an impact assessment framework to 1) produce a comprehensive record of the impact the March/April and July 2018 tephra falls of Manaro Voui volcano had on buildings in Ambae. This record will contribute towards the currently limited empirical data available on buildings impacted by tephra fall, and thus 2) develop an understanding of the vulnerability of buildings in Pacific Island nations to tephra fall. This has been achieved through the following five objectives:

- *Objective 1: Establish the risk context of the volcanic crisis for the Island of Ambae 2017/18 with a focus on the built environment*
- *Objective 2: Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano.*
- *Objective 3: Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*
- *Objective 4: Analyse the impact of tephra fall on buildings in Ambae and how construction characteristics or environmental factors may have influenced individual building vulnerabilities to tephra fall.*
- *Objective 5: Evaluate the effectiveness of mitigation techniques used by Ambae residents to minimise the impact buildings sustained from tephra fall and assess suitability of these methods for future eruptions in other areas exposed to tephra fall.*

1.4 RESEARCH METHODOLOGY AND THESIS STRUCTURE

This thesis is comprised of five chapters, utilising the scientific approach (Section 1.4.2.2) as a conceptual structure for the thesis.

- Chapter One establishes the framework for the thesis, defining the aims and objectives.

- Chapter Two establishes the risk context on Ambae, provides an overview the eruption history of Manaro Voui, and reviews literature on tephra fall and the impact it has on society, with a particular focus on buildings and how this information is used in volcanic risk assessments.
- Chapter Three provides a chronology for the 2017/18 eruption period of Manaro Voui and the methodology used to develop tephra fall hazard models for the March/April and July 2018 tephra falls.
- Chapter Four outlines the methodology used to create a building inventory which characterises the construction of buildings observed during field visits to Ambae. This is followed by the methodology used to record building damage from tephra fall and identify some of the vulnerabilities that can be identified from this record. The chapter is concluded with observed mitigation methods used to minimise building impacts from tephra fall.
- Chapter Five concludes the key findings from Chapter Four and how this thesis contributes to the current understanding of building vulnerability and impact to tephra fall. It reflects upon the methodologies used to achieve this thesis' aims and provides future research opportunities.

Chapter two: Literature review

2.1 Introduction

This chapter establishes the risk context on Ambae, leading up to and during the 2017/18 eruption period of Manaro Voui with a focus on Ambae's built environment. This is done by reviewing the three components of risk (hazard, exposure and vulnerability) relevant to the impact the complex volcanic crisis has had on buildings, addressing the thesis' first objective;

- *Objective 1: Establish the risk context of the volcanic crisis for the Island of Ambae 2017/18 with a focus on the built environment*

2.2 Ambae island and Manaro Voui volcano overview

Section 2.2 is structured in two parts. The first provides the risk context on Ambae, identifying the demographics, lifestyle, governance, the built environment, climate and historic disasters. The risk context is fundamental for this thesis to understand the environment on Ambae, in terms of who and what was exposed, leading up to, and during, the 2017/18 eruption period of Manaro Voui. The second part provides an overview of Manaro Voui volcano, identifying the geological setting, eruption history and how volcanic risk is managed on Ambae. This provides insight into the hazards Manaro Voui has produced in the past, and how they relate to the hazards produced during the 2017/18 eruption period and how the volcanic crisis was managed.

2.2.1 Ambae Island

Ambae Island is the emergent portion of Manaro Voui volcano, with rugged topography caused by volcanic features such as scoria cones and lava flows scattered across the island. Most of Ambae is covered in thick tropical rainforest vegetation that extends from the summit to the coast, except where people have developed their villages and plantations. Multiple stream channels drain rainwater from the summit of Manaro Voui to the coast, but due to Ambae's climate, water does not always continuously flow throughout the year.

2.2.1.1 Demographics

Prior to the 2017/18 eruptive period of Manaro Voui, Ambae's population was 10,858 (Vanuatu National Statistics Office [VNSO] 2016), most of whom were situated along or close to the coastline of Ambae (Figure 2.1). Ambae has a youthful population, with 47% of the island's population younger than the age of 20 (Figure 2.2). Almost all of Ambae's population (> 99%) are of Melanesian ethnicity and Ni-Vanuatu nationality, with < 1% of people being Non-Melanesian or not from Vanuatu (VNSO, 2016). Two main languages are spoken on Ambae with the areas in which each are spoken being split between the east and west of the island (Tarisesi, 1998). There are 12 known dialects of these two languages (Tarisesi, 1998), but Bislama, Vanuatu's national language, is the lingua franca (Cronin et al. 2004). English and French, Vanuatu's other official languages, are taught at schools, but their usage in rural areas of Ambae is low (Cronin et al. 2004). Approximately 89% of children attend primary school, but only 26% of children continue on to secondary school (Cronin et al. 2004).

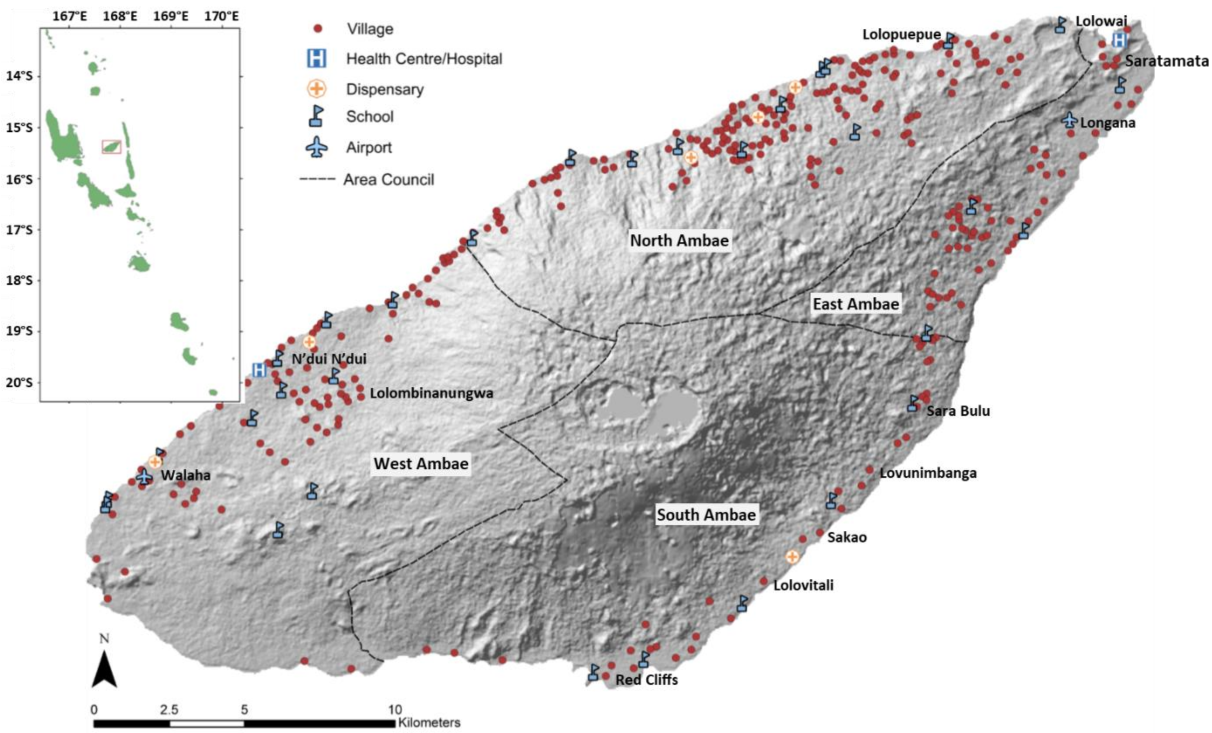

Figure 2.1 Village and key facility distribution showing both where people and buildings are concentrated around Ambae. Adapted from MapAction (2016).

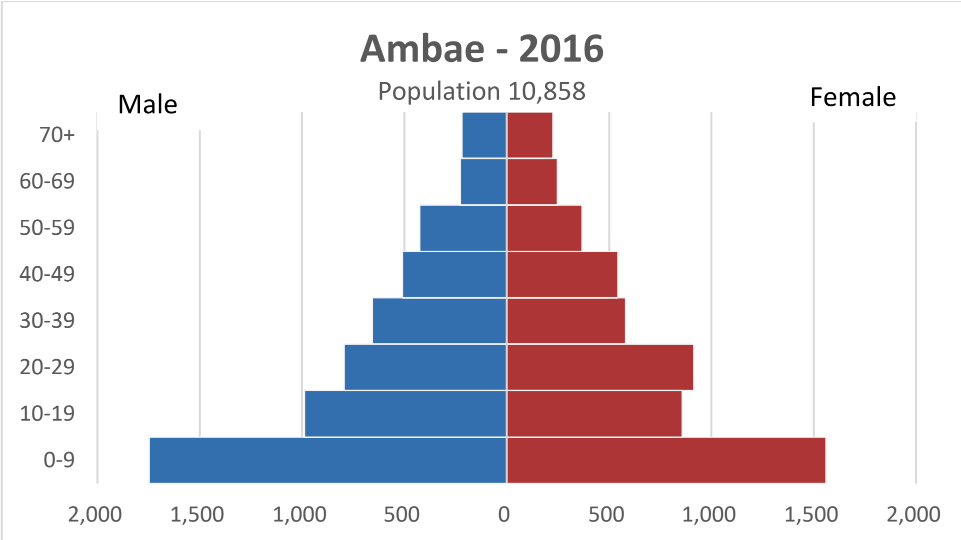

Figure 2.2 Population graph of Ambae, Vanuatu Data source: VNSO (2016)

2.2.1.2 Lifestyle

Most families in Ambae live in private detached households on land held from customary land tenure (land owned by indigenous communities and administered in accordance to their Kastom/traditional custom) (VNSO, 2016). Families are mostly self-sufficient, relying primarily on subsistence farming as their source of food, supplemented by food sold in small local shops. Key food crops grown by households are kumala (sweet potato), island cabbage, yam, taro, banana, paw paw and manioc (cassava) but a wider range of other fruit, vegetables and nuts are also grown. There are 40 tilapia (a type of freshwater fish) ponds that provides an alternative source of protein (Nimoho & Turot, 2017).

The cultivation of cash crops is the main primary industry on Ambae, and is the source of income for approximately 59% of households (VNSO, 2016). The most common cash crops on Ambae are coconut (for producing copra), kava and cocoa plantations. Other sources of income come from public sector employment (14%), remittances from relatives employed on other Vanuatu islands (5%), and privately owned businesses (15%) (VNSO, 2016). Most households also own livestock, which are either sold as supplementary sources of income, consumed by the household, or used through Kastom practices.

Appendix B provides the data sourced from Vanuatu's post-Cyclone Pam census (2015) used to identify the lifestyle on Ambae used to develop the risk context.

2.2.1.3 Governance

The islands Ambae, Maewo and Pentecost comprise the Penama province, one of six provinces of Vanuatu (Figure 1.1). Saratamata, the capital of the Penama province, hosts the Provincial Council that oversees the province's administration (Cronin et al. 2004), and promotes regional autonomy in the area. Elected and appointed representatives for women, youths, chiefs and churches make up the council, along with officers which represent the government departments of police, women's affairs, public works and education, and health (Cronin et al. 2004).

2.2.1.4 Built environment

Ambae's built environment is co-located with its population, with a higher density of buildings near the coast, including community structures such as schools, churches, health centres and general stores. Compared to Western societies, Ambae's built environment is very different. Approximately 51% of residential buildings have traditional thatch roofs (VNSO 2016) and are likely of traditional construction, but most community structures are of non-traditional construction. Local roads passable by off-road vehicles connect various settlements, but no roads circumnavigate the island and access in and out of some areas is restricted to boats. Following heavy rainfall and strong winds many roads become impassable due to washouts and fallen vegetation blocking access. Two operational airstrips, Longana and Walaha, located at either end on the island, provide services on and off the island with scheduled commercial flights to nearby Espiritu Santo Island. Solar panels provide individual households with electricity used to power lights in the evenings and charge cell phones and there is limited use of diesel generators as alternative sources of electricity. Telecommunications on Ambae is limited to cell phone service with cell towers distributed around the island, providing cell phone service to most populated areas. Most drinking water (88%) is sourced from rainwater tanks or wells that use gutter systems on building rooftops to collect rain water (VNSO, 2016). The remaining 12% of drinking water is supplied to households through pipe systems, or sourced directly from a stream, spring, or underground bore (VNSO, 2016). No reticulated wastewater systems are present and 96% of households have pit latrine-style toilets (VNSO, 2016).

2.2.1.5 Climate

Located between 13 and 20°S latitude, Vanuatu has a tropical-maritime climate with a high humidity (>80%) and uniform temperatures (Nemeth & Cronin, 2007). The wet season occurs between November and April, with the dry (and cooler) season between May and October. During the dry season the south-easterly trade winds are most prevalent, but during the wet season wind directions are more variable and tropical cyclones common (Nemeth & Cronin, 2007). Between 23 and 30 tropical cyclones affect Vanuatu each decade, with 3-5 causing severe damage to the landscape and vegetation (Nemeth & Cronin, 2006).

Annual rainfall in Vanuatu ranges between 1,500 mm and 4,000 mm each year, with the northern islands tending to be wetter than the southern islands (World Bank Group, n.d.). Topographic highs influence the rainfall pattern on some islands in Vanuatu, with Manaro Voui creating an orographic rainfall effect. During the dry season, orographic effects from the south easterly trade winds bring rainfall to the south and east of Ambae, and create drier conditions in the north and west.

2.2.1.6 Previous disaster history

Tropical cyclones and volcanic eruptions from Manaro Voui are the two hazards that have contributed to disasters in Ambae's recorded past. Though 3-5 tropical cyclones impact Vanuatu each decade, the long latitudinal span of the archipelago means that not all tropical cyclones necessarily impact Ambae as the tropical cyclone may only cross the southern or northern-most islands. Typical impacts of tropical cyclones include damage to crops, damage to buildings ranging from minor to complete destruction, contamination of water supplies, loss of telecommunications, blocked access ways and flight disruptions. Cyclone Pam in 2015 was the last cyclone to cause damage on Ambae, and destroyed a minor proportion of buildings (Table 2.1).

Table 2.1 Number of household dwellings completely damaged by Cyclone Pam 2015. Data source VNSO (2016)

Region	Dwelling completely damaged by cyclone	
	Yes	No
West Ambae	29	798
North Ambae	37	762
East Ambae	95	431
South Ambae	18	312

The impact past eruptions from Manaro Voui have had on Ambae are not well recorded. Lava flows from an eruption around 1670 and lahars that accompanied an eruption in 1870 both destroyed villages and resulted in fatalities (Eissen et al. 1991; Cronin et al, 2004), but the number of fatalities is unknown.

2.2.2 Manaro Voui

Manaro Voui (also known as Aoba, Ambae, Lombenben and Manaro) is the volcano that through a history of eruptions has built the island of Ambae. The observed history of a volcano's eruptive history, combined with interpretations of the tephrostratigraphic record and products of past eruptions are used to understand what hazards a volcano may produce in the future (Blong, 1996). Understanding Manaro Voui's past, and recognising the hazards it can produce, combined with knowing what is exposed on Ambae is essential for volcanic disaster risk management to be effective on Ambae.

2.2.2.1 Geological setting

The islands that make up the Vanuatu archipelago are the emergent portion of a 700 km long ridge that overlies the Pacific plate as the eastward dipping Indo-Australian plate subducts below (Robin et al. 1993) (Figure 2.3). The North and South New Hebrides Trenches formed by the subduction zone lay west of Vanuatu and are separated by the d'Entrecasteaux zone (Robin et al. 1993) (Figure 2.3). The d'Entrecasteaux zone is where the trench has been buried by sediment as a submarine chain extending from northern New Caledonia that subducts below the Pacific plate (Collot & Fisher, 1991; Robin et al. 1993). On average, the Indo-Australian plate subducts towards the east below the Pacific plate at a rate of approximately 10 cm/year. However, the d'Entrecasteaux zone subducts obliquely, towards the north, almost parallel to the trench at a rate of approximately 2.5 cm/year, generating stresses in the area (Collot & Fisher, 1991) (Figure 2.3).

Ambae is the emergent portion of Manaro Voui, a geologically active basaltic shield volcano and Vanuatu's largest volcano, rising 3900 m from the seabed to reach an elevation of 1496 m above sea level (Robin et al. 1993; Rouland et al. 2001; Cronin et al. 2004; Nemeth et al. 2006). The oldest rocks found exposed on Ambae have been dated at approximately 1.7 million years (Warden, 1970). Manaro Voui volcano is elongated along a NE-SW trending rift zone (Ambae fracture zone) producing the ellipsoid-shaped island. The Ambae fracture zone is formed by the stresses applied in the area due to the d'Entrecasteaux zone subducting more slowly and at an angle to the neighbouring plate boundary (Robin et al. 1993).

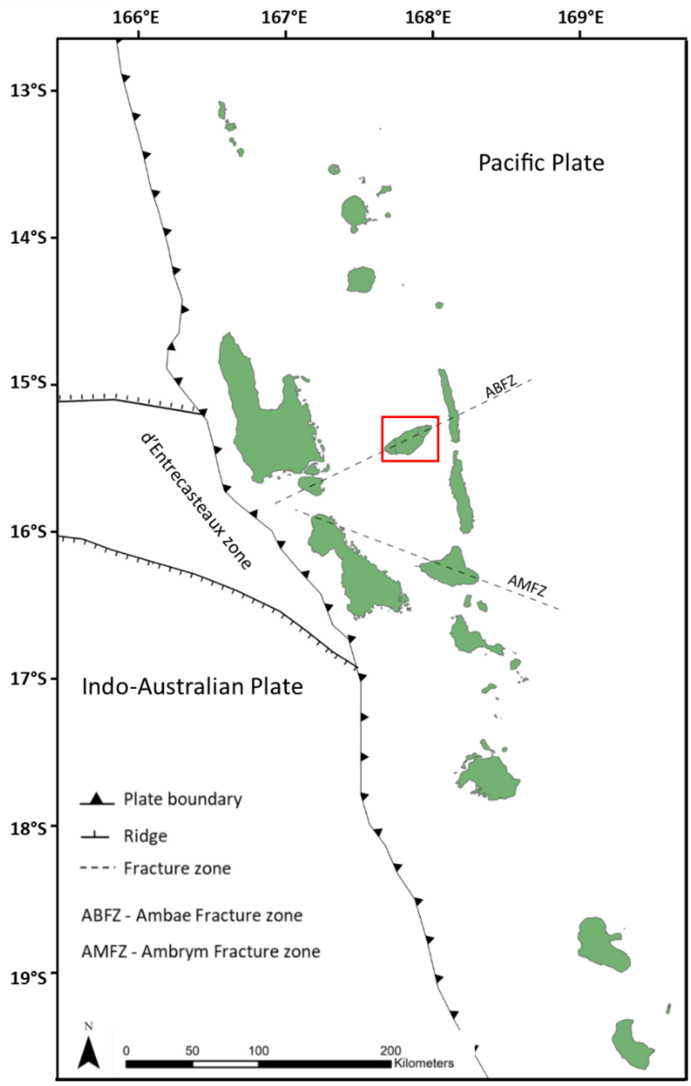

Figure 2.3 Simplified tectonic setting of the Vanuatu archipelago that forms the Ambae Fault Zone (ABFZ)

2.2.2.2 Manaro Voui eruption history

There are few studies on Manaro Voui's eruptive history since its emergence above sea level, approximately 0.7 million years ago (Cronin et al. 2004). The earliest building phase of Manaro Voui is characterised by voluminous, basaltic, lava flows interstratified with thin (< 1 m) pyroclastic units comprising of ash and lapilli (Warden, 1970; Eggins, 1993; Robin et al. 1993). The exception is the

Lomala Pyroclastics, a thick sequence (estimated 60 m) of ash and lapilli exposed on the northern slopes of Manaro Voui (Warden, 1970). This suggests that previous activity from Manaro Voui ranges from quiet, effusive to large, explosive Plinian eruptions. The presence of pyroclastic deposits increases towards the summit of the volcano and are overlain by agglomerates (Warden, 1970). Scoria cones scatter the NE-SW trending rift zone, marking sites of previous Strombolian activity, but become maars where the rift zone reaches the sea (Eggins, 1992).

The present summit morphology of Manaro Voui is the result of a caldera-forming eruption approximately 400 years ago, producing the two concentric calderas (Figure 2.4). The basaltic magma composition and lack of explosive pumiceous deposits from Manaro Voui suggest that it was not a large explosive eruption that formed the two summit calderas. Instead, it is more likely that the formation of the two calderas was quiet, and formed by a substantial outpouring of lava at lower depths through flank eruptions, combined with a substantial volume of material erupted at the summit (Warden, 1970; Eggins, 1993; Nemeth et al. 2006). Since their formation, the two summit calderas have been partially filled by three lakes; Lake Vui, Manaro Lakua and Manaro Ngoro (Warden 1970, Rouland et al. 2001), with the current active vent located below central Lake Vui (Nemeth et al. 2006) (Figure 2.4). There is some discussion as to whether Lake Vui sits within a broad cone that surrounds the summit crater in the centre of the inner caldera, or is a third smaller caldera itself (Warden, 1970).

Since the formation of the two calderas, Manaro Voui's activity has been characterised by multiple explosive eruptions, lahars and gas-release events (Cronin et al. 2004). A notable eruption in 1870 AD produced tephra falls and lahars which washed out exposed villages causing fatalities (Cronin et al. 2004). In 1670 AD an isolated western-flank effusive eruption occurred, producing lava flows that destroyed N'dui N'dui village (Cronin et al. 2004). Between the 1870 eruption and 1991, activity from Manaro Voui has been characterised by fumarole emissions, with the exception of a possible eruption in 1914 that produced lahars (Rouland et al. 2001). The eruption period that began in September 2017 producing complex intermittent tephra falls (Section 3.2) is part of a much longer eruption sequence that began with volcanic unrest in 1991 and eruptions in 1995, 2005-2006, 2011 and 2016. These intermittent tephra falls impacted a large area of Ambae, damaging buildings and crops, contaminating water sources and threatening human health and safety.

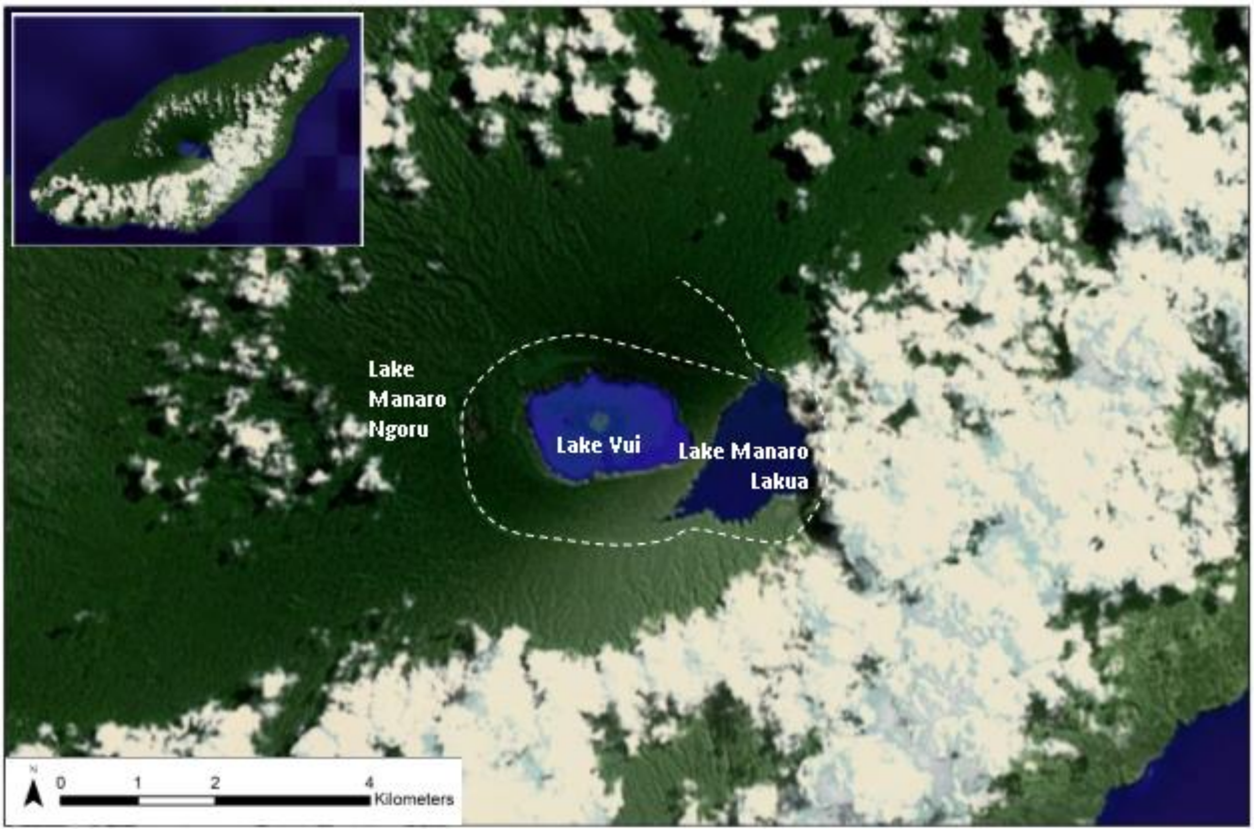

Figure 2.4 Satellite imagery of the summit area of Manaro Voui showing the three lakes and outline of the concentric calderas. Adapted from Nemeth et al. (2006)

Table 2.2 provides a summary of the recorded eruption history and activity of Manaro Voui identifying the Volcanic Explosivity Index (VEI), and the volcanic hazards produced from each eruption. The VEI is a nine scale index ranging from 0 (non-explosive Hawaiian eruption) to 8 (Ultraplinian eruption) based on both the volume of erupted material and eruption column height (Newhall & Self, 1982). Manaro Voiu's recorded historical eruptions have ranged from VEI 1 (< 10^4 m^3 erupted material, 0.1-1 km eruption column height) to VEI 3 (< 10^7 m^3 erupted material, 3-15 km eruption column height). A detailed eruption chronology for the 2017/18 eruption period of Manaro Voui is provided in Chapter Three (Section 3.2).

Table 2.2 Recorded historical eruptions and activity of Manaro Voui

Activity date	VEI	Volcanic hazards produced	References
1575	Unknown	• Flank lava flows • Tephra falls	Warden (1970); Eissen et al. (1991); Rouland et al. (2001); Cronin et al. (2006)
1670	2	• Flank lava flows • Pyroclastic cone formation	Warden (1970); Cronin et al. (2006)
1870	2	• Tephra falls • lahars	Warden (1970); Cronin et al. (2004)
1914 (unconfirmed)	Unknown	• Tephra falls • lahars	Eissen et al. (1991); Rouland et al. (2001)
July 1991	N/A	• Anomalous boiling activity within the caldera lakes.	Robin et al. (1993); Rouland et al. (2001); Global Volcanism Program (1991)
3rd March 1995	2	• Tephra fall	Rouland et al. (2001); Global Volcanism Program (1995)
27th November 2005 – February 2006	2	• Tephra fall • Pyroclastic cone formation	Global Volcanism Program (2005); Global Volcanism Program (2006)
December 2009 – April 2010	N/A	• Volcanic degassing.	Global Volcanism Program (2013)
4th June 2011	1	• Tephra fall	Global Volcanism Program (2013)
10-11th July 2011	1	• Tephra fall	Global Volcanism Program (2013)
September 2017 – November 2018	3	• Tephra fall • Gas emissions • Lahars • Pyroclastic cone formation	Global Volcanism Program (2018a); Global Volcanism Program (2018b); Global Volcanism Program (2019)

2.2.2.3 Volcanic disaster risk management on Ambae

Manaro Voui's observed eruption history is short and not well documented. Detailed analysis and interpretation of ancient eruptions are limited, however the impacts from past eruptions and current ongoing activity from Manaro Voui highlight the need for DRM actions. Vanuatu's Meteorological and Geohazards Department (VMGD) have two volcano-seismic monitoring stations and a web-camera installed on Manaro Voui monitoring volcanic activity. Both seismic and camera monitoring systems deliver a near-real time feed of information to VMGD's office in Port Villa and to their website. Seismic activity can be a sign that magma is ascending, so seismic stations are used to monitor earthquakes in volcanic areas to identify potential precursors to an eruption. Before the eruptions in July 2018, VMGD (with support of GNS Science, New Zealand) installed 6 additional temporary seismic stations. The expanded seismic monitoring network allows the determination of the location and depth of nearby earthquakes, providing insight into how magma may be ascending within Manaro Voui.

Based on the information provided by the seismic stations and visual observations (webcam and on-island VMGD employee), VMGD use a Volcanic Alert Level (VAL) system to describe Manaro Voui's current state of unrest or eruption (Table 3.2). When the VAL is changed a Volcano Alert Bulletin (VAB) is released outlining the current state of the volcano, why the volcano is in this state, how the current state may change, and safety zones based on the current level of activity (see https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin for VMGD's VAB archive). This information is shared publicly and is used by the Vanuatu's Ministry of Climate Change and National Disaster Management Office (NDMO) along with any other requested information to inform emergency management decision making and disaster responses (Figure 2.5).

Volcanic Alert Bulletins for Manaro Voui, provided by VMGD to Vanuatu's NDMO are then passed on to Penama's Provincial Council. Based on this information, the provincial council can activate its Emergency Operations Centre (EOC) to assist with preparing for, or coordinating a response to a volcanic event. Penama EOC's head office is located in Saratamata, Ambae (Figure 2.1), but smaller, temporary, EOC offices can be set up elsewhere on Maewo or Pentecost, the other two islands that make up the Penama Province. During a small event the provincial council may be able to coordinate their own response and recovery without the need for support from a national level. For larger events, where the required response exceeds what the provincial council is capable of, Penama's EOC can receive support from Vanuatu's NDMO, Vanuatu's NDMO may then also decide to activate their own National Emergency Operations Centre (NEOC) to support with response operations (NDMO, 2013).

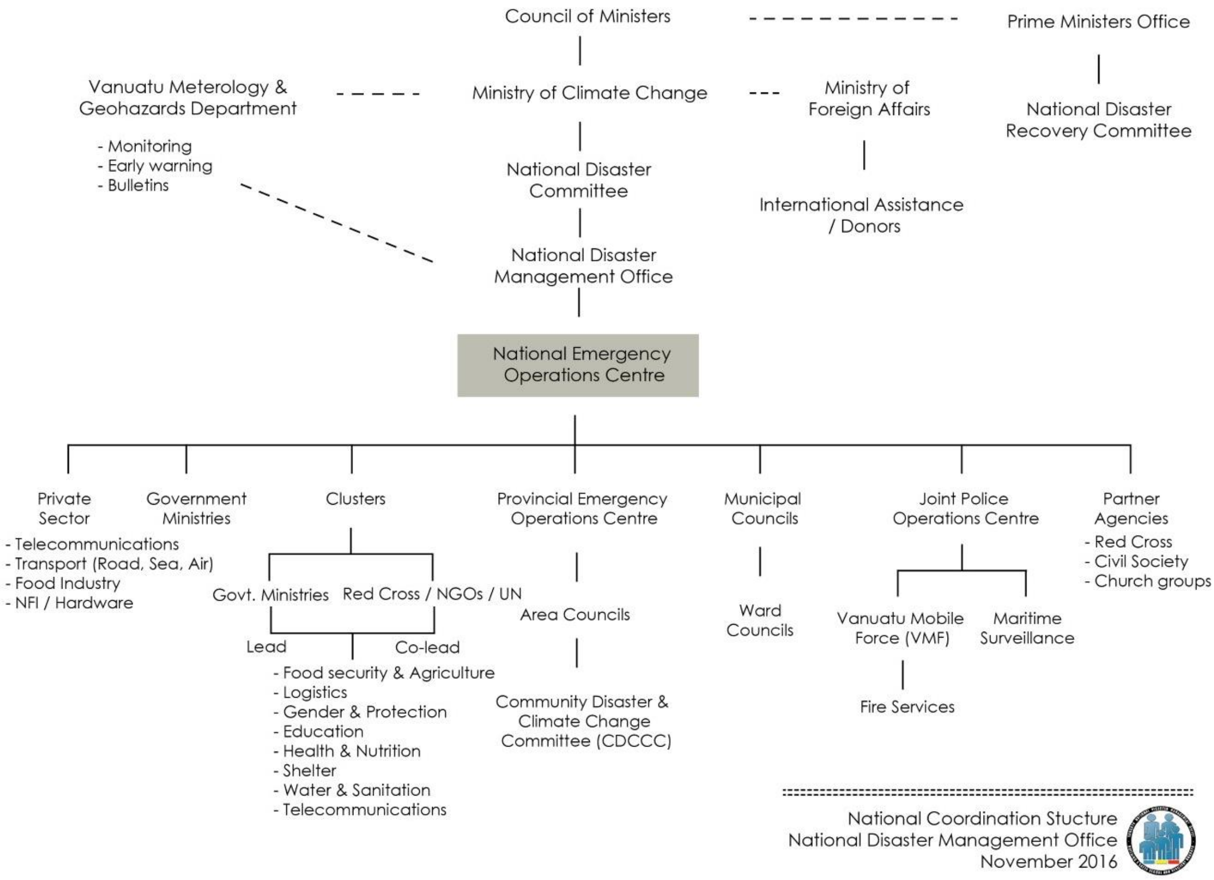

Figure 2.5 Vanuatu's national coordination structure during a large emergency response (Figure source: NDMO, 2017)

All emergency response operations are coordinated and managed by the Penama EOC (Penama Provincial Disaster Management Plan, 2002-2003). While most decisions regarding the emergency response are also made by the Penama Provincial Council, some decisions, such as whether to evacuate or relocate a large population are made by the Council of Ministers. However, regardless of the decision made by the Council of Ministers, Penama EOC still manage and coordinate this decision into their emergency response. Foreign aid and international assistance from other countries and Non-Governmental Organisations (NGOs) are sourced by Vanuatu's Ministry of Climate Change, but once received it is the role of the Penama EOC to organise and distribute this aid.

2.3 TEPHRA FALL HAZARDS

Tephra fall hazards have been produced throughout Manaro Voui's eruption history and eruptive activity during the 2017/18 eruption period. The following section presents the scientific community's current understanding of tephra fall risk in terms of the hazard, the building assets on Ambae and the buildings' inherent vulnerabilities to tephra fall, contributing to this thesis' first objective;

- *Objective 1: Establish the risk context of the volcanic crisis for the Island of Ambae 2017/18 with a focus on the built environment*

Using the information provided a methodology is proposed to record the impact of the 2017/18 eruption period of Manaro Voui on the built environment.

2.3.1 Tephra fall hazard

Tephra fall is the most widespread volcanic hazard (Jenkins et al. 2015) and can be both damaging and disruptive to exposed populations (Blong, 1984). The term 'tephra' is used to describe all airborne, fragmented products of explosive volcanic eruptions (Blong, 1984; Sparks et al. 1997; Alloway et al. 2013). Tephra particles range in sizes from blocks and bombs (> 64 mm), lapilli (2-64 mm) and ash (< 2 mm). Tephra fall is the term used to describe the process of airborne particles that are dispersed by falling out of an ash cloud formed by an eruption column and does not include tephra particles that are dispersed through ballistic trajectories (Blong, 1984). Further information on the processes of how tephra is formed and how tephra fall is dispersed is provided in Appendix C.

The thickness of the tephra fall deposit has historically been the most common metric used to assess hazard intensity (Jenkins et al. 2015). Tephra fall hazard models are typically presented as tephra isopach maps, which give the tephra thickness in a given area. More recently in the literature, there has been a shift toward assessing the intensity of tephra fall hazard through the metric 'tephra mass loading' (mass of deposited material per unit area) rather than deposit thickness. Tephra mass loading is more informative when considering the impacts tephra fall has on buildings (Jenkins et al. 2015) as it is the weight of tephra that will cause structural elements of a building such as rafters or purlins to fail. However, tephra loading is not the only mechanism by which tephra can impact exposed assets (Jenkins et al. 2015). Physical characteristics such as soluble surface composition, particle size, density, abrasiveness and environmental factors such as humidity and weather can also be informative when trying to determine the potential impact of tephra fall to exposed assets (Wilson et al. 2012). The physical and chemical properties of tephra vary greatly, and depend on magma composition, volatile content and composition, size and style of the eruption, and atmospheric conditions. Further information on the different physical and chemical properties of tephra is provided in Appendix C.

2.3.2 Tephra fall impact

The following section provides a summary of current understanding of how tephra fall impacts buildings. A brief summary of the impacts tephra fall has on human health, infrastructure and agriculture is provided in Appendix D. The current understanding of how tephra fall impacts society is variable, and gaps which still need to be addressed remain. Substantial work has gone into understanding the impact tephra fall can have on human health. However, more recently there has been a shift as it has become apparent the crucial role buildings, infrastructure and agriculture plays within a society's ability to function, particularly in a post disaster environment.

2.3.2.1 Buildings

Buildings play a crucial role in society and are a key part of a person's life, providing shelter and places for employment. They are more than an economic asset and can be considered a place that represents safety, a livelihood and may hold great sentimental value to an individual. When considering the impact tephra fall may have on a building, it is important to look beyond the physical damage buildings sustain and consider a building's functionality as a place where people live or work. A building's capability to function is an important consideration for decision-makers, particularly during evacuations, as even though there may be no immediate damage due to structural damage a building may still be unsafe for habitation (Wright & Johnston. 2010).

Tephra fall can directly impact buildings in four different ways (Figure 2.6). These mechanisms are;

1. Structural damage to the building caused by static loading (e.g. roof collapse through rafter or purlin failure) (Spence et al. 1996, 2005; Pomonis et al. 1999; Blong, 2003).
2. Non-structural damage to the building envelope (e.g. damage to gutters by static loading, roof corrosion by acid leachates (Blong, 1984)).

3. Damage or disruption to building services (systems that enable a building to function e.g. electricity, Heating, Ventilation and Air Conditioning (HVAC) systems, water and power supplies (Blong, 1984, 1996; Hayes et al. 2019)).
4. Contamination of building interiors and exteriors.

A building's loss in functionality is dependent on all four of these impacts which all act within an interdependent system. Such impacts can seriously reduce a building's ability to provide safe and functional habitation for occupants (Deligne et al. 2017). Whether or not it is safe for people to remain living in their houses is one of the considerations that influence evacuation decisions (Wright & Johnston, 2010).

Figure 2.6 Four mechanisms by which tephra fall directly impacts buildings. (a) Structural damage (b) non structural damage to gutter system (c) disruption to the solar panel functionality (electricity source) (d) contamination of a building interior and exterior (Photo credit Susanna Jenkins)

2.3.3 Volcanic risk assessment for buildings; current state

Understanding how tephra fall impacts buildings and the associated consequences to society is necessary for understanding tephra fall risk and developing vulnerability models (Jenkins et al. 2015). In order to produce meaningful volcanic risk assessments, there is a need for robust vulnerability models which link hazard intensity with a probability of damage (Blong, 1984). In volcanic risk assessments, vulnerability models are typically the weakest element (Jenkins et al. 2015), especially when compared to building vulnerability models used in earthquake or flood risk models. There are few studies available that provide the empirical data essential for informing the development of robust vulnerability models (e.g. Spence et al. (1996); Blong (2003); Hayes et al. (2019)). Consequently, the development of building vulnerability models for tephra fall, which link hazard intensity with a probability of damage have been supplemented with experimental and theoretical studies (Jenkins et al. 2014). Therefore, it is crucial that the data on how buildings were impacted by tephra fall recorded as a part of this thesis is made available, and appropriately presented to enable the development of these robust vulnerability models, essential for meaningful risk assessments.

Current vulnerability models and volcanic risk assessments for buildings all focus on the expected structural performance of the building. This focus on structural performance stems from a strong emphasis on life safety when volcanic DRR was first developing as roof collapse from tephra loading was one of the few mechanisms that could directly cause injury or loss of life. In vulnerability models and risk assessments buildings have been considered an 'asset' and losses are typically considered in terms of occupant vulnerability or extent of damage a building may sustain (e.g. Pomonis et al. 1999; Biass et al. 2016; Blong et al. 2017; Leder et al. 2017).

Only most recently has the perception of a building shifted from an asset to part of a person's livelihood. Homes and businesses represent places of safety and livelihoods and any disruption to their function as a place of safety or livelihood can have a negative impact on a society. Tephra fall is capable of causing disruption without causing any damage to buildings. Disruption from tephra fall can be direct (e.g. contaminating building interiors creating a health hazard) or indirect (e.g. restricting accessibility due to unsafe driving conditions or cordons). Therefore, it is important to consider how tephra fall may disrupt a building's functionality within society in addition to the damage tephra fall may cause.

2.3.4 Past building impact studies

Studies of tephra fall impact on buildings from past volcanic eruptions are limited when compared to the extensive studies on building impacts from other hazards such as earthquake and flood (Blong, 1996, 2003; Jenkins et al. 2015). There are only three comprehensive studies of building damage from tephra fall from Spence et al. (1996) in Castillejos, Philippines (1991), Blong (2003) in Rabaul, Papua New Guinea (1994) and Hayes et al. (2019) in the area surrounding Calbuco, Chile (2015). The lack of post eruption studies is partially attributed to the low frequency of large eruptions that impact urban areas, the logistical and political challenges associated with entering impacted areas, and ethical and cultural considerations (Jenkins et al. 2014; Hayes et al. 2019). The rest of this section summarises the three studies on the impact past tephra falls have had on buildings and identifies where gaps remain in the scientific communities understanding of building vulnerability to tephra falls.

2.3.4.1 Tephra fall building impacts, Mt Pinatubo 1991

Spence et al. (1996) was the first systematic study of the impact of tephra fall on buildings in the town of Castillejos, the Philippines, following the 1991 Mt Pinatubo eruption. These authors drew from post-earthquake damage assessment studies, which used a modification of the Medvedev–Sponheuer–Karnik (MSK) earthquake intensity scale to assess building damage. The MSK scale estimates the severity of ground shaking during an earthquake based on observed impacts in the affected area. The modified MSK scale for assessing earthquake building damage consists of six defined levels of building damage which Spence et al. (1996) modified to suit building damage sustained from tephra fall. These authors recognised that it was the load of tephra on the roof structure that was resulting in building damage, though no relationship between hazard intensity and the extent of damage is presented: instead the relationship between building characteristics and extent of damage is presented. Key building vulnerabilities identified in this study were non-residential buildings, timber framed buildings, long span roof, and high-pitched roof structures that were not pitched enough to overcome the frictional resistance of the roof material(Spence et al. 1996).

2.3.4.2 Tephra fall building impacts, Tavurvur & Vulcan 1994

Blong (2003) studied the impact of tephra fall from the 1994 Tavurvur and Vulcan eruptions on buildings in Rabaul, Papua New Guinea. The data was mostly collected by loss assessors, commissioned engineers, quantity surveyors and building professionals, who evaluated building damage for insurance purposes, but was also supported by field observations. Buildings recorded were all constructed after WWII and were biased towards better-quality buildings that were insured and did not include uninsured buildings. Using the six-point damage state framework developed by Spence et al. (1996), Blong (2003) related building damage to tephra load, highlighting key vulnerabilities in construction characteristics. By relating the extent of damage to the hazard intensity, Blong (2003) noted a positive correlation between increasing building damage and tephra load, a trend which has been applied to building vulnerability models in succeeding literature.

2.3.4.3 Tephra fall building impacts, Calbuco 2015

Hayes et al. (2019) is the most recent contribution on post-eruption impacts of tephra fall on buildings. This study investigated tephra fall and lahar impacts on buildings following the 2015 Calbuco eruption, Chile. Data was sourced from observations, damage classifications (for insurance purposes) and photos taken during a governmental damage assessment, supported by observations and interviews made by the authors. The same six point damage state framework methodology used in previous studies was adopted with minor modification to the damage definitions to best encapsulate the data set. Unlike the two previous studies, this study also assessed the quality and reliability of collected and acquired data. Hayes et al. (2019) highlighted the complexities of using secondary data sources, most notably the data applicability, detail, completeness and consistency.

2.3.4.4 Tephra fall impact knowledge and data gaps

The seminal works by Spence et al. (1996), Blong (2003) and Hayes et al. (2019) have been invaluable in improving the quality of building vulnerability models for damage from tephra fall with empirical evidence. However, all three studies focussed on the physical damage tephra fall caused to the local building stock which were engineered structures. This meant they could not explicitly consider traditional buildings (made of bamboo and thatched materials) nor how the impact may evolve throughout a multi-phase eruption or how tephra fall may disrupt a building's functionality. In volcanic impact literature there has been strong focus on engineered buildings that use predominantly timber, masonry or concrete construction materials and how volcanic hazards may impact them (e.g. Pomonis et al. 1999; Jenkins et al. 2014; Maqsood et al. 2014). There has been limited research on traditional thatch buildings constructed from raw construction materials such as bamboo, tree trunks and leaves, despite their strong prevalence in less-developed subsistence communities. The exception is Jenkins et al. (2014), who used expert judgement and structural engineering calculations to derive vulnerability functions for traditional Nipa thatch dwellings in the Philippines due to the absence of their being any empirical data. This work suggested that the traditional Nipa thatch dwellings were more vulnerable to loading from tephra fall than other non-traditional buildings.

There are crucial gaps that still need to be addressed in the scientific community's understanding of how tephra fall impacts buildings. A vulnerability model for traditional buildings, informed by empirical data from post-eruption impacts is yet to be developed. This restricts the ability to produce robust volcanic risk assessments for traditional buildings that inform DRR decisions. The impact that the 2017/18 eruption period of Manaro Voui had on buildings has the potential to provide the empirical data and insight necessary to begin filling these gaps.

Spence et al. (1996), Blong (2003) and Hayes et al. (2019) all utilised photographs as a way to capture and record the impact tephra fall had on buildings. The environment on Ambae during the 2017/18 eruption period was dynamic and continually evolving, and in order to capture the impact the intermittent tephra falls were having on buildings, a rapid methodology of field data collection was necessary. A methodology that uses photographs of buildings to rapidly collect data in the field and later combine with satellite imagery to locate each photographed buildings on Ambae is proposed to record the impact of tephra falls on buildings. This record of building damage is developed to provide insight into the following knowledge gaps and achieve this thesis objectives:

- What is the vulnerability of traditional construction style buildings to tephra fall and what are their failure methods under tephra loading?
- What building mitigation methods ae effective a minimising the impact of tephra fall on buildings in tropical environments, including traditional buildings
- How may tephra fall disrupt the habitability of a building without causing any damage and how could habitability be maintained?
- How may building vulnerability evolve during a prolonged or complex multi-phased eruption?

2.4 Summary

Chapter Two has presented a literature review that established the risk context on Ambae during the 2017/18 eruption period of Manaro Voui, and provided information on the current understanding of tephra fall processes, how tephra fall can impact society and how we are currently using this information in volcanic risk assessments, achieving this thesis' first objective;

- *Objective 1: Establish the risk context of the volcanic crisis for the Island of Ambae 2017/18 with a focus on the built environment*

Ambae is a developing island whose residents live mostly subsistence lifestyles. The geological setting of Ambae exposes its population to volcanic hazards produced by Manaro Voui. Vulnerability models and volcanic risk assessments have focused on the damage tephra fall can inflict on buildings, but it is equally important to consider how tephra fall can disrupt a building's functionality without causing damage. Past building impact assessments have contributed invaluable data for the development of vulnerability models, however these assessments have focused on the physical damage to engineered buildings from tephra fall. There remains a gap in the scientific community's understanding of how tephra fall impacts traditional buildings. Traditional buildings are common in developing countries and play a crucial role in the livelihoods of those people. This thesis is the first empirical dataset for traditional Pacific buildings impacted by tephra fall. It allows for a new understanding of building vulnerability from tephra fall and provide the empirical data foundation required to begin developing robust vulnerability models used in volcanic risk assessments used to inform DRR decisions.

Chapter three: Manaro Voui 2017/18 eruption chronology and tephra fall hazard model development

3.1 Introduction

The following chapter is spilt into two sections. The first provides an overview of the 2017/18 eruption period of Manaro Voui volcano. The second presents the methodology used to develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui, to address this thesis' second objective;

- *Objective 2: Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano.*

Hazard models are one of the three inputs necessary for completing an impact assessment (Figure 1.3). The tephra fall hazard models are therefore essential for this thesis to be able to achieve its overall aims to; 1) produce a comprehensive record of the impact the March/April and July 2018 tephra falls of Manaro Voui volcano had on buildings in Ambae, and 2) develop an understanding of the vulnerability of buildings in Pacific Island nations to tephra fall.

Three field visits to Ambae collected the data necessary to develop tephra fall hazard models of the March/April and July 2018 tephra falls of Manaro Voui and record the damage Ambae buildings sustained from these tephra falls (Table 3.1). The first (April 2018) and third (August 2018) field visits were led by Vanuatu's Meteorological Geohazards Department (VMGD) who had requested international collaboration following the March/April and July 2018 tephra falls. Both field visits were part of a humanitarian support response as per the request from VMGD following public concerns about further roof collapse, air quality deterioration and water supply contamination. The second field visit in July 2018 was part of a longitudinal study of the 2017/18 Manaro Voui eruption period by a team interested in the physical processes occurring on Ambae. All three field visits were constrained by the time they had available in the field, therefore a methodology that rapidly collected the necessary data, but also provided a broad coverage across Ambae was implemented.

Table 3.1 Summary of the three field visits to Ambae in 2018 outlining field visit focus, data collected, time of visit and days since the damaging tephra falls.

Field visit and focus	Dates on Ambae	Data collected	Days since damaging tephra falls
Field visit 1 - International humanitarian support of VMGD (GNS Science, University of Canterbury)	• 17-21 April	• Tephra deposit measurements • Building photographic survey	• 34 days since 15-16/03 tephra fall west • 30 days since 21/03 tephra fall south • 9 days since 9-11/04 tephra falls north
Field visit 2 - Longitudinal research (GNS Science, University of Auckland)	• 18-25 July	• Tephra deposit measurements	• 22 Days since 01/07 tephra fall west • Present during 20-22/07 tephra falls east-south east
Field visit 3 - International humanitarian support of VMGD (GNS Science, University of Canterbury, Massey University, Nanyang Technological University)	• 4-9 August	• Tephra deposit measurements • Building photographic survey	• 35 days since 01/07 tephra fall west • 14 days since 16-25/07 tephra falls east-south east

3.2 Manaro Voui 2017/18 eruption

The following section provides an overview of the 2017/18 eruption of Manaro Voui. Table 3.2 summarises the volcanic processes, volcanic hazard impacts and the emergency response that occurred throughout the 2017/18 eruption period of Manaro Voui with a detailed eruption chronology provided in Appendix E. It contributes to the thesis' second objective '*Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano*' by identifying the specific tephra falls within the complex multi-phase eruption that resulted in damage to buildings.

The 2017/18 eruption period was split into four eruption phases (Vanuatu National Disaster management Office [NDMO]. 2018) characterised by Manaro Voui's Volcanic Alert Levels (VAL) (Table 3.3) tephra falls and Ambae's population movements (Figure 3.1). It is recognised that within each eruption phase of Manaro Voui there were many tephra falls (Figure 3.1), however only a few of these tephra falls reached Ambae residents and impacted buildings (Table 3.4). It is these few individual tephra falls that are represented in the tephra fall hazard models, rather than a single tephra fall model that represents the entire 2017/18 eruption period of Manaro Voui.

Table 3. 2 Summary of the 2017/18 eruption period of Manaro Voui volcano

	Time period	Volcanic hazards	Volcanic hazard impacts	Emergency response actions
Phase One	Sept – Nov 2017	• Formation, destruction and reconstruction of pyroclastic cone surrounding the active vent • Lava flows constrained to within the summit caldera • Small eruptions producing tephra plumes (<5 km plume height) • Gas emissions • Acid rain west and south of the active vent	• Drinking water sources contaminated by tephra and acid rain • Acid rain burning crops • Tephra inhibiting crops from photosynthesising • Physical crop damage from tephra • Indirect impacts to crops from livestock, theft, pests and neglect of care • No reported building damage	• 1st-28th September Penama EOC coordinates emergency response evacuating villages in the west and south to evacuation centres • 26th September, State of Emergency declared • 29th September compulsory whole-island evacuation issued • 22nd October-1st November repatriation period • Information of volcanic hazards and how to minimise their impacts disseminated to Ambae residents • Continual monitoring of Manaro Voui
Phase Two	Dec 2017 – Feb 2018	• Heightened degassing and steam emissions • Acid rain west and south of the active vent • Few, small tephra producing eruptions (<5 km plume height)	• Drinking water sources contaminated from acid rain • Acid rain burnt crop leaves • No reported building damage	• Information of volcanic hazards and how to minimise their impacts disseminated to Ambae residents • Continual monitoring of Manaro Voui
Phase Three	Feb – Mid-Mar 2018	• Activity from Manaro Voui increased • Multiple small eruptions producing tephra fall (<5 km plume height) • Continued gas emission • Acid rain west and south of the active vent	• Villages exposed to tephra fall only received very thin tephra deposits • Drinking water sources contaminated by tephra and acid rain • Acid rain burnt crop leaves	• Information of volcanic hazards and how to minimise their impacts disseminated to Ambae residents • Continual monitoring of Manaro Voui's activity • Drinking water samples and tested for evidence of tephra contamination
	15th Mar – 12th Apr 2018	• Three large eruptions (5-10 km plume height) producing thick tephra fall deposits towards the west (15-16th March) south (21st March) and north, northeast (9-11th April)	• Buildings impacted by tephra, some buildings exposed to thick tephra fall sustained structural damage • Drinking water sources contaminated by tephra and acid rain	• Villages exposed to thick tephra fall self-evacuated to evacuation centres • Rations and water distributed to evacuated villages • Impact is assessed and response plan developed

		• Small intermittent eruptions producing small tephra falls (<5 km plume height) • Continued acid rain west and south of the active vent	• Thick tephra deposit buried and physically damaged crops and limited their ability to photosynthesise	• Evacuation from worst affected areas west and south of the vent becomes compulsory • Continued monitoring of Manaro Voui's activity
	13th Apr – End Apr	• Gas and steam emissions from the vent • Acid rain west and south of the active vent • No tephra producing eruptions	• Drinking water sources contaminated from acid rain • Acid rain burnt crop leaves	• State of Emergency issued until the 23rd July 2018 • Continued planning for a compulsory whole-island evacuation • Continued monitoring of Manaro Voui's activity
Phase Four	1st – 27th July	• Two large eruptions producing thick tephra fall deposits towards the west (1st July) (5-10 km plume height) and east, southeast (16th-27th July) (5-15 km plume height) • Small intermittent eruptions producing small tephra falls (<5 km plume height) • Large degassing event of SO2 towards the east	• Buildings impacted by tephra, some buildings exposed to thick tephra fall sustained structural damage • Drinking water sources contaminated by tephra and acid rain • Thick tephra falls caved in the tops of some tanks • Thick tephra deposit buried and physically damaged crops and limited their ability to photosynthesise • Some livestock were dying from lack of food and water • Tephra deposited on neighbouring islands Maewo and Pentecost	• State of Emergency lapsed and was extended to the 26th Sept. • Villages exposed to thick tephra fall self-evacuated to evacuation centres • Compulsory whole-island evacuation issued on the 26th July and completed 13th Aug. • Food, water and construction materials supplied to the evacuated population • Continual monitoring of Manaro Voui's activity
	28th July – November	• Manaro Voui's activity began to decrease • Small eruption on 1st Sept and 20th Oct. (<5 km plume height)	• Further indirect impacts to crops from livestock and lack of care while people were evacuated	• State of Emergency extended to the 26th Nov. • People could not return to Ambae until the end of the State of Emergency • Once people began returning to Ambae basic services were restored e.g. schools opened

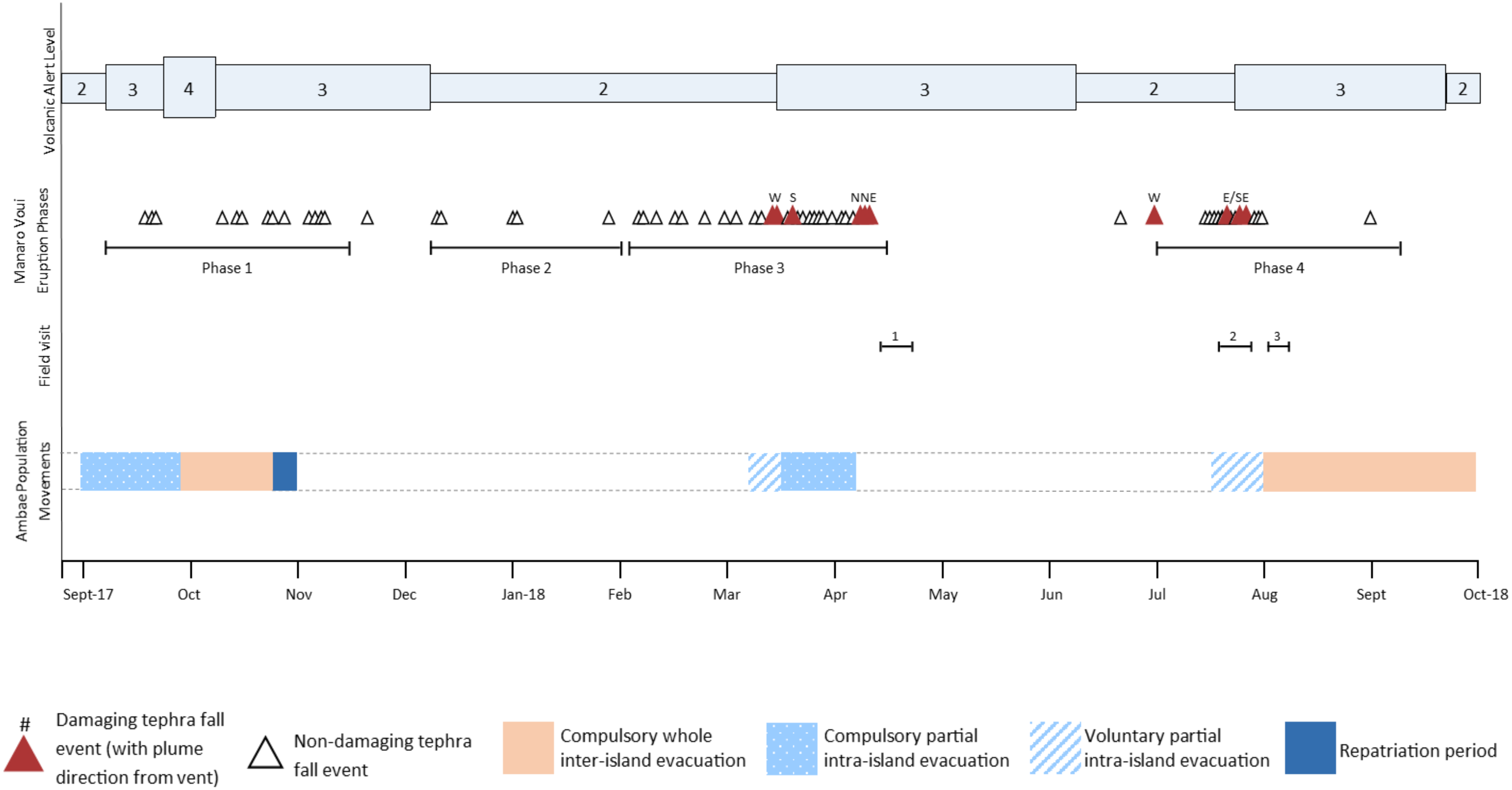

Figure 3.1 Timeline of the Volcanic Alert Levels (defined in Table 3.2), eruption phases and the tephra falls that damaged exposed villages, Ambae field visits and Ambae population movements for the 2017/18 Manaro Voui eruption period.

Table 3.3 Vanuatu Volcanic Alert Level System used by Vanuatu's Meteorology and Geohazards Department to define the current status of each of its volcanoes and guide responses (VMGD, 2014).

Title	**Alert Level**	**Description Area/ Distance**
Normal	0	No signs of change in the activity, limited danger
Signs of Volcanic Unrest	1	Notable signs of unrest, possible danger near eruptive vents
Major Unrest	2	Danger around the crater rim and specific area, notable/large unrest, considerable possibility of eruption and also chance of flank eruption
Minor Eruption	3	Danger within caldera, volcanic cone and other specific area, possibility of moderate eruption and also chance of flank eruption
Moderate Eruption	4	Danger on volcanic cone, caldera and all island, possibility of very large eruption and also chance of flank eruption
Very Large Eruption	5	Danger beyond caldera, on entire and surrounding islands and also chance of flank eruption

Table 3.4 Tephra falls produced by Manaro Voui that reached Ambae residents and resulted in damage to buildings

Date of building damaging tephra falls	**Dominant tephra plume direction (from vent)**
March 15th – 16th 2018	West
March 21st 2018	South
April 9th – 11th 2018	North northeast
July 1st 2018	West
July 16th – 27th 2018	East southeast

3.3 Manaro Voui March/April and July 2018 Tephra Fall Hazard Model Development

The purpose of this section is to outline the methodology used to develop the tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui. The tephra fall hazard models are presented, and the limitations of their development identified achieving this thesis' second objective;

- *Objective 2: Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano.*

3.3.1 Methodology for Manaro Voui 2017/18 tephra fall hazard model development

The tephra fall hazard models were constructed from in-field measurements of the tephra deposit collected by volcanologists from VMGD, GNS Science, University of Canterbury, University of Auckland, Massey University and Nanyang Technological University during the three field visits to Ambae. Each tephra deposit measurement was located geospatially as point locations in a geographic information system. Time constraints and accessibility restrictions meant that the number of in-field tephra deposit measurements that could be collected were limited. Therefore, field teams opted for a broader coverage of tephra measurements across Ambae, rather than detailed measurements in a few areas. Gaps between the tephra deposit measurements were supplemented with estimates from alternative data sources such as field photos, field team members' notes and Ambae residents. The supplementary estimates of the tephra deposit were located geospatially and ranked with a level of confidence depending on their expected representation of the actual tephra deposit thickness for their location (Table 3.5).

Table 3.5 Summary on how tephra deposit thickness measurements were categorised based upon a confidence that they are representative of the actual tephra deposit from the March/April or July 2018 tephra falls

Tephra deposit measurement source	Expected tephra deposit representation	Level of confidence
In-field measurements by volcanologists	Thickness is accurately measured and location taken from GPS locations	High
Photograph estimates	Thickness is inferred without measuring but location is accurate from photograph coordinates	Moderate
Volcanologist in-field estimates	Thickness is inferred without measuring but location is accurate from a combination of GPS locations, timestamps on field notes, photographs or identifiable features both in field and in satellite imagery.	Moderate
Ambae resident estimates	Thickness is inferred without measuring and location is often vague	Low

Isopachs for the March/April and July 2018 tephra falls were developed by drawing isolines of a specific tephra deposit thicknesses using the located points of measured and estimated tephra deposit thicknesses to help guide the isolines (Figure 3.2). These isopachs could only identify a broad range for the tephra thickness in any given area (e.g. tephra thickness between 10-19 mm). Therefore, the tephra isopachs were further developed into a detailed isopach where a single tephra thickness value could be identified for any location on Ambae, rather than a broad range. The detailed isopachs were compared to control points of known tephra fall thicknesses from the in-field measurements. Not all field measurements were used as control point as some locations showed evidence of having been disturbed (e.g. erosion) but were still used to help infer the tephra fall hazard models. The detailed isopachs were adjusted accordingly until the tephra thicknesses they identified were within 5mm of the control points of known tephra fall thicknesses.

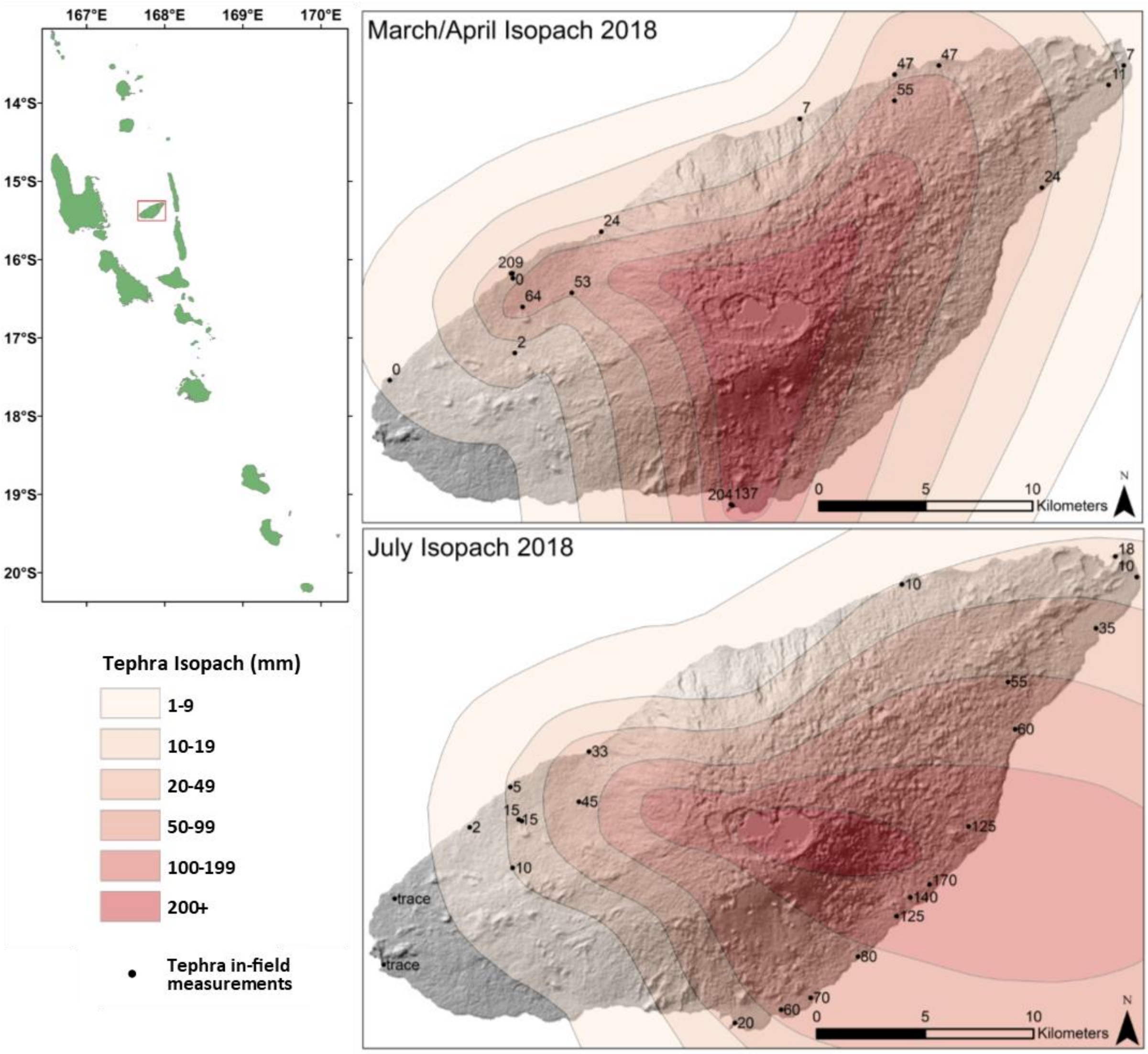

Figure 3.2 Manaro Voui March/April 2018 tephra fall hazard *models*

3.3.2 Results of the Manaro Voui March/April and July 2018 tephra fall hazard models

3.3.2.1 March/April 2018 tephra fall hazard model

In March/April 2018, three damaging tephra falls occurred (Figure 3.2). The first tephra plume travelled west of the vent on the 15-16th March, followed by a plume to the south on the 21st March and then lastly to the north-northeast on 9-11th April. Smaller intermittent tephra falls occurred during this time also. However, these tephra falls were either not large enough to reach villages visited during the field visits, or only deposited thin (<5 mm) deposits of tephra fall, causing no damage to buildings.

3.3.2.2 July 2018 tephra fall hazard model

In July 2018, two damaging tephra falls occurred (Figure 3.2). The first plume travelled west of the vent on the 1st July, followed by a plume towards the east-southeast during the 16-25th July. As for the March/April period, there were smaller, intermittent but non-damaging tephra falls during this time.

3.3.3 Limitations of the March/April and July 2018 tephra fall hazard models

This thesis has used the thickness of the tephra deposit as the hazard intensity measure to relate the hazard to building damage. This is despite the recommendation by both Spence et al. (1996) and Blong (2003) that tephra loading is a more appropriate hazard intensity measure than thickness as it is the weight of tephra on a building that can cause structural damage.

The load a tephra deposit applies to a building per unit area depends upon the volume (found by multiplying the area by the tephra depth) and the bulk density of the tephra. Only two *in situ* measurements of the tephra deposits bulk density was recorded in the field by the second field visit team due to time constraints. Both of these measurements came from the same location, but at different stages during the same prolonged tephra fall on the 21-22 July 2018. The tephra densities measured were 0.97 and 0.44 g/cm^3 (970 and 440 kg/m^3) taken after 7.5 and 15.5 hours of tephra fall deposition respectively. The remaining tephra bulk densities collected were not in situ and were analysed later by the second field visit team in a lab. Tephra samples analysed in the lab showed spatial variability in their density, varying between 0.90 and 1.68 g/cm^3 (900 and 1680 kg/m^3) (Figure 3.3). The variability in tephra fall density was attributed to the disturbance of the tephra sample when collected for lab analysis, complexity of the eruption phases, spatial and temporal variation between individual tephra falls, the time between tephra fall and sample collection and the influence of climate and weather. With the limited number of measured tephra densities, and the variation amongst them, it was decided that the tephra fall deposit thickness would be used for the tephra fall hazard model, rather than tephra loading.

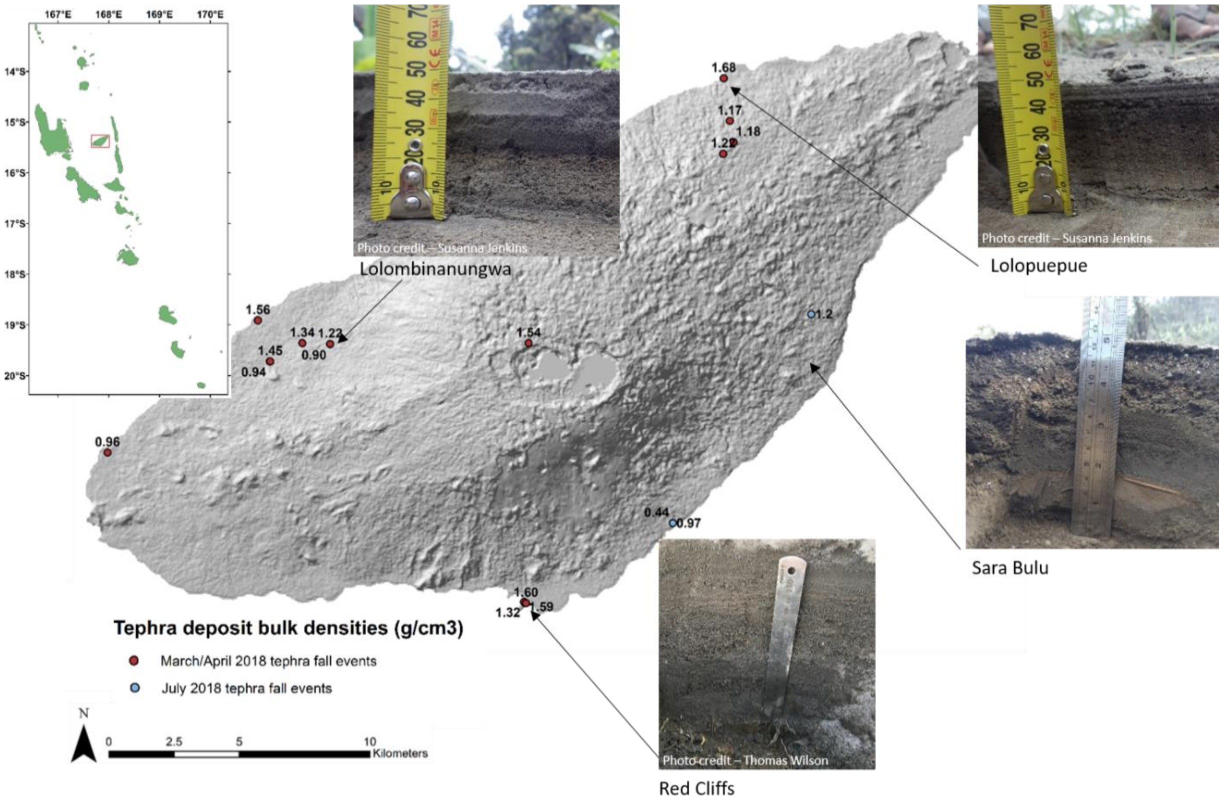

Figure 3.3 Tephra sections taken following the July 2018 tephra falls, showing the spatial variation of the tephra deposit. Combined with the limited samples that were collected in the field, variation in the tephra deposit made it difficult to model the tephra fall density for both the March/April and July 2018 tephra falls.

3.3.3.1 Tephra deposit spatial and temporal variation

Visual profiles taken of the tephra deposit during the field visits showed that particle sizes from the tephra falls varied across Ambae. Tephra bulk composition, particle size distribution, water content and degree of compaction will influence the bulk density of a tephra deposit and can result in variations across and area exposed to the same eruption (Spence et al. 2005). The tephra deposit section recorded at Lolopuepue (location AOB 514) was exposed to a single tephra fall and showed what appears to be a relatively homogenous deposit. This is compared to the tephra deposit section recorded in Sara Bulu (location AOB 518) where there were multiple tephra falls, which created distinctive tephra layers of varying grainsizes (Figure 3.3). With the limited tephra deposit sections recorded, it was not possible to correlate or map individual tephra layers present within some of the tephra deposit sections thus making it more challenging to model the tephra deposit density distribution across Ambae.

3.3.3.2 Time delay recording tephra deposit

Once tephra is deposited it will begin to compact, reducing its thickness and increasing its density (Scasso et al. 1994). The compaction of the tephra deposit is a function of time and depositional dynamics, but can also be influenced by the environment (e.g. from rain or wind) (Segerstrom. 1950; Blong et al. 2017). This is an important consideration as there was up to a month between the deposition of tephra fall and the field teams measuring the thickness of the tephra deposit (Table 3.1). This means that compaction of the tephra deposit would have already occurred, and the tephra deposit measurements are minimum thicknesses. An example is Lolombinanungwa village. The March/April 2018 tephra deposit was measured to be 50 mm thick during the first field visit in April 2018. Taking into consideration the time delay between the deposition of the tephra and its measurement, it is expected that the tephra deposit had already undergone some compaction. Later during the third field visit in August 2018, the same deposit was remeasured at 40 mm, having undergone a further 10 mm of compaction between the two field visits.

3.3.3.3 Climate and weather

Variation in the rainfall and wind patterns around Ambae can also contribute to differences in the tephra deposit density. Added moisture to tephra fall deposits can increase their density (Macedonio and Costa. 2012), but excess rain may result in the tephra being washed away. December to April is the wet season for Vanuatu, followed by a dry May to November. The southeasterly trade winds Ambae is exposed to create an orographic effect with a wetter environment in the south and east and a drier, windier environment in the north and west. Following the July 2018 tephra falls the influence of climate was evident in the tephra deposit. Volcanologists have commonly reported tephra fall deposits forming a crustal layer on the surface when exposed to water (e.g. rain) (Tarasenko et al.

2019). In Sara Bulu village, East Ambae, where there was still rainfall despite it being the dry season, a crustal layer on the surface of the tephra deposit had formed (Figure 3.3). Surface crustal layers can create an impermeable boundary that water cannot infiltrate, encouraging surface run-off and inhibit the re-emergence of plants buried by the tephra (Tarasenko et al. 2019). The same surface crustal layer was not seen in the west where there had not yet been any rain since the tephra was deposited.

3.4 Summary

Chapter Three provided an overview of the 2017/18 eruption of Manaro Voui volcano and the methodology used to develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui, achieving this thesis' second objective;

- *Objective 2: Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano.*

It was crucial that the chronology of the 2017/18 eruption period of Manaro Voui volcano was understood, because despite the numerous tephra falls recorded there were only five that were recorded as having damaged buildings (Table 3.3). This chronology informed the time periods for which the tephra fall hazard models represent. The March/April and July 2018 tephra fall models are used in the impact assessment to relate the damage buildings sustained to the tephra fall hazard to begin understanding the vulnerabilities of the buildings on Ambae.

CHAPTER FOUR: DIRECT AND LONGITUDINAL TEPHRA FALL IMPACTS TO AMBAE BUILDINGS

4.1 INTRODUCTION

The following chapter is split into three sections which address the following thesis objectives;

- *Objective 3: Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*
- *Objective 4: Analyse the impact of tephra fall on buildings in Ambae and how construction characteristics or environmental factors may have influenced individual building vulnerabilities to tephra fall.*
- *Objective 5: Evaluate the effectiveness of mitigation techniques used by Ambae residents to minimise the impact buildings sustained from tephra fall and assess suitability of these methods for future eruptions in other areas exposed to tephra fall.*

Section 4.2 presents the methodology used to develop a building inventory for Ambae from photographic surveys taken during field visits to Ambae. The results from the building inventory are further developed in section 4.3. Section 4.3 presents the methodology used to develop the building inventory into a comprehensive record of the damage buildings sustained from the March/April and July 2018 tephra falls of Manaro Voui, addressing objective three of this thesis. The results from the comprehensive record of building damage are presented and analysed to determine how building construction characteristics and environmental factors influenced building vulnerability to tephra fall, addressing objective four of this thesis. Finally, section 4.4 evaluates the effectiveness and applicability of building mitigation methods observed on Ambae to future tephra falls addressing objective five of this thesis.

4.2 AMBAE BUILDING INVENTORY

The following section presents the methodology used to process a photographic survey of buildings on Ambae into a building inventory that records the location and construction characteristics of buildings observed. This is the first step to achieving objective 3 of this thesis;

- *Objective 3: Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*

4.2.1 Methodology for developing a building inventory for Ambae

Photographic surveys of buildings on Ambae were collected from the first and third field visits following the March/April and July 2018 tephra falls. During the first field visit in April 2018, four broad building construction typologies were identified on Ambae (Figure 4.1). These included three permanent building construction typologies and a fourth temporary building typology. The building typologies identified were; Traditional (T), Hybrid construction (X), Non-traditional construction (N) and Temporary (E) structures. Each building construction typology is further split into sub-categories to accommodate for variations within each construction typology (Table 4.1).

Developing broad building typologies during the first field visit increased the processing efficiency for each building identified in a photograph. This allowed for a larger photographic survey to be collected during the third field visit which recorded 74% (n=435) of buildings in the final building inventory. This proved beneficial for data collection as a greater breadth of buildings exposed to the multiple tephra falls of Manaro Voui were recorded. Since photographs became the primary source of building data, crowd-sourced photographs collated by VMGD, and organised by village, were also included in the building inventory. The photographs collated by VMGD were valuable to the final building inventory as they included photographs from villages inaccessible during the field visits due to time constraints and roads made impassable by a combination of road degradation from heavy rainfalls and debris flows (Figure 4.2).

Figure 4.1 Four broad building construction typologies present on Ambae at the time of the 2017/18 eruption period; Traditional (T), Hybrid construction (X), Non-traditional construction (N) and Temporary (E).

All buildings identified in a photograph were located geospatially using satellite imagery. Locations were determined using the GPS co-ordinates of each photograph file and a GPS track taken in the field which could link the time a photograph was taken to a GPS location at that point of time. Buildings recorded in the inventory from crowd-sourced photographs did not have GPS co-ordinates. Therefore, they were located using satellite imagery and the village name the photograph was taken from, as recorded by VMGD when they collated the photographs.

Each building identified and located was allocated a construction sub-category assigning the building frame (wall and roof), wall cladding and roof cover. Construction characteristics, including roof pitch, presence of verandas, gutters and any other external features not included in the basic construction category were assigned based on the photographs. The quality or quantity of photos for each building would sometimes generate uncertainty in the assignment of the exact location and construction characterisations of each building recorded. To recognise and record any uncertainty associated with the photographs, a confidence level and data quality indicator was assigned to each building, adopting the methodology used by Hayes et al. (2019).

Table 4.1 Ambae building typologies identified in the building inventory and the common building characteristics associated with them

	Code	Construction sub-category	Building description
Traditional	Ts	Traditional short span	Primarily wooden posts and bamboo for wall and roof framing, typically split bamboo wall cladding and high pitch thatch roof cover (may have additional corrugated sheet metal)
	To	Traditional outhouse	Same as Ts but smaller (occupies one) with flat roof
Hybrid Construction	X1	Modern wall, traditional roof	Timber framed wall, typically corrugated sheet metal cladding and traditional roof as described in Ts
	X2	Traditional wall, modern roof	Timber framed roof, typically with corrugated sheet metal cover with traditional wall frame as described in Ts
	Xw	Mixed wall construction	Concrete-filled reinforced breeze block basal wall frame and remaining half timber, typically split bamboo cladding and timber framed roof with corrugated sheet metal cladding.
Non-traditional Construction	Nt	Timber frame	Timber framed walls and roof, high pitch corrugated sheet metal roof and typically timber, plywood or corrugated sheet metal walls
	Nb	Reinforced breeze block frame	Concrete-filled reinforced breeze block walls with a timber framed roof and corrugated sheet metal roof cover
	Nc	Reinforced concrete pillars	Primary reinforced concrete wall frame (with or without minor reinforced breeze block walls) with a timber framed roof and corrugated sheet metal roof cover
Temporary shelter	E	Temporary structure	Fibreglass frame with a canvas cover tied down with rope

4.2.2 Results of the Ambae building inventory

4.2.2.1 Building Typology Distribution

A total of 589 buildings were surveyed on Ambae and recorded in the building inventory. The proportion of each building construction sub-category recorded in the building inventory is summarised in Table 4.2. From the building inventory, traditional short span (Ts) and reinforced breeze block framed (Wb) buildings were the most prevalent construction sub-categories recorded, representing approximately 70% of the building inventory combined. It is stressed that this is not a complete building inventory for Ambae and therefore the proportions of the building construction sub-categories may not be representative of all buildings present on Ambae. It is also recognised that there was a sampling bias associated with the locations visited and photographed. Because of the humanitarian focus of the first and third field visits, villages that were impacted by heavy tephra fall, requested by VMGD, accessible or visited by previous field teams were prioritised.

Table 4.2 Building distribution by building construction sub-category

	Code	Construction sub-category	No. in sample	% of sample (n=589)	
Traditional	Ts	Traditional short span	252	43.3%	44.0%
	To	Traditional outhouse	4	0.7%	
Hybrid Construction	X1	Modern wall, traditional roof	8	1.0%	17.5%
	X2	Traditional wall, modern roof	21	3.6%	
	Xw	Mixed wall construction	76	12.9%	
Non-traditional Construction	Wt	Timber frame	47	8.0%	36.3%
	Wb	Reinforced breeze block frame	162	27.3%	
	Wc	Reinforced concrete pillars	6	1.0%	
Temporary shelter	E	Temporary structure	13	2.2%	2.2%

The distribution of the building construction typologies varied spatially across Ambae. Villages with schools, health centres, churches and general stores (e.g. Lolowai & Lolopuepue) had a higher proportion of buildings of non-traditional construction than villages that did not have these facilities (e.g. Sakao) (Figure 4.2). Villages highlighted in Figure 4.2 were villages where all buildings were recorded in the building surveys as observed in both the field and from satellite imagery. Villages such as Lolowai, the site of Ambae's only hospital and Lolopuepue, one of Ambae's boarding schools, had a larger proportion of buildings of non-traditional construction typologies, than traditional buildings (Figure 4.2). This is in contrast to the villages Sakao, Lovunimbanga and Lolombinanungwa that are not sites of schools or health centres and had a larger proportion of traditional buildings than buildings of non-traditional construction.

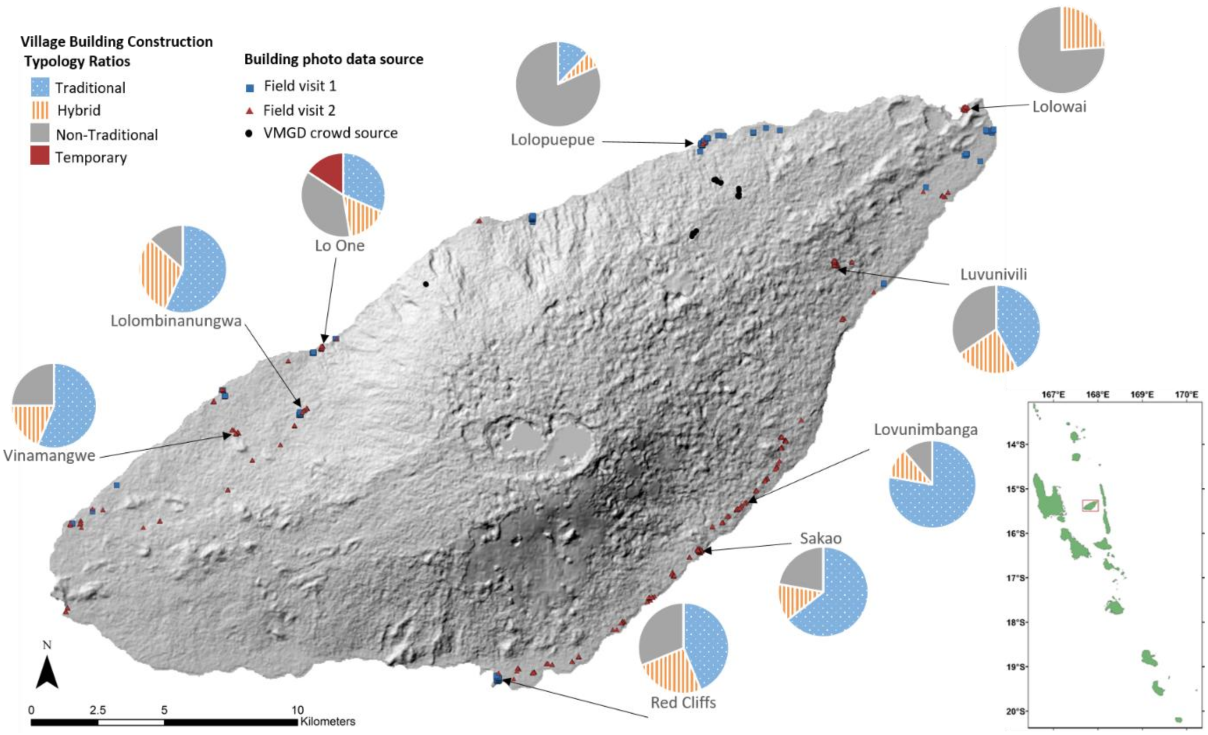

Figure 4.2 Photographic survey sources and the variation of the building typology distribution by village. Highlighted villages are ones which had all buildings recorded in the building inventory as seen whilst in the field and through satellite imagery.

4.3 Ambae Building Damage

The following section presents the methodology used to develop the building inventory from the previous section to produce a comprehensive record of the damage each building sustained from tephra fall. This record of building damage is analysed to begin developing an understanding the vulnerability of buildings on Ambae to tephra fall. This addresses the following two thesis objectives:

- *Objective 3: Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*

- *Objective 4: Analyse the impact of tephra fall on buildings in Ambae and how construction characteristics or environmental factors may have influenced individual building vulnerabilities to tephra fall.*

4.3.1 Methodology for recording building damage from tephra fall on Ambae

Once a building was located and construction characterised, a description of the damage from tephra fall visible in photographs and from in-field observations was recorded (Figure 4.3). Based on the description of damage, a damage state was allocated to each building as defined in Table 4.3. The damage state criteria was adapted from Hayes et al (2019) so that each damage state criteria was simplified and relevant for the building typologies on Ambae, which unlike buildings in Calbuco, Chile, do not have electrical systems, air conditioning units or tile roofs. A conservative approach was applied when allocating building damage states, meaning if the data did not allow for a building's damage state to be definitively categorised between two states, the higher damage state was allocated.

Each building was allocated a tephra fall thickness based upon their location relative to both the March/April and July 2018 isopachs. Photographs from the first field visit in April 2018 showed that many building roofs had already been, or were in the process of being cleared of tephra. Because of the time between the March/April and July 2018 tephra falls it was assumed that any tephra that accumulated on a roof during the March/April 2018 tephra falls was removed (either by people, wind or rain) before the July 2018 tephra falls. Therefore, the assumption was made that the damage a building sustained from tephra fall came from either the March/April or July 2018 tephra falls, rather than an accumulation of the two. Using anecdotal accounts and the time period which photographs were taken, the tephra fall thickness that most likely caused the recorded building damage was allocated to each building. It is this tephra thickness that is used to relate building damage to the tephra fall hazard intensity. A confidence level and data quality indicator was assigned based on the quality and assuredness of anecdotal accounts, in the same manner to how the uncertainty of the building's location and construction was recorded.

Table 4.3 Building damage state framework used to categorise building damage from the 2017/18 Manaro Voui eruption period. Framework adapted from Hayes et al. (2019)

Damage state	Description	Characteristics	Example
DS0	No Damage	• No Damage	
DS1	Light damage or damage to non-structural elements	• Damage to gutters • Damage to contents • Dents or minor slumping in roof cover	 *Photo Susanna Jenkins*
DS2	Moderate damage but vertical structure and roof supports intact	• As above • Bending or excessive damage (without collapse) to up to half of the roof covering • Little or no damage to roof support trusses and rafters • Damage to roof overhangs or verandas • Interior requires repair	 *Photo Susanna Jenkins*
DS3	Severe damage to the roof and supports	• As above • Bending or excessive damage (with or without collapse) to more than half of the roof covering • Damage to any single principle roof supports and/or some damage to walls • Severe damage or partial collapse of roof overhangs or verandas	 *Photo VMGD*
DS4	Partial collapse of the roof and supports	• As above • Collapse to less than half of roof covering and principal roof support(s) • At least half of external and/or internal walls deformed or collapsed	
DS5	Building collapse	• As above • Collapse of roof, principle roof supports and/or supporting external walls over more than half of floor area of building	 *Photo Susanna Jenkins*

Ridge board snapped

Rafters have failed.

All external walls have collapsed

DS=5

Roof structure has collapsed, ridge board and rafters have failed.

One external wall has failed with timber boards framing part of the wall damaging the reinforced breeze block

DS=5

3/4 of the gutters along length of building have failed or fallen off

Gutters remaining are full of ash

DS=1

Figure 4.3 Examples of photographs used to describe the damage buildings sustained from tephra fall with the damage descriptions and corresponding damage state given to them

4.3.2 Results of the damage to buildings from the Manaro Voui March/April and July 2018 tephra falls

The following section presents the results from the record of the damage buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano. It provides an overview of the distribution of building damage across Ambae and how building construction typology influenced the distribution of damage. The relationship between tephra fall thickness and a building's damage state is presented for each of the three permanent building typologies (traditional, non-traditional and hybrid). This is followed by observations of longitudinal damage, building failure mechanisms and non-structural damage that buildings sustained on Ambae.

4.3.2.1 Building Damage Distribution

Just over half (56%) of the buildings surveyed on Ambae showed no signs of damage (DS0; n=330), while just over a tenth (12%) of buildings had partial or complete roof collapse (DS4-5; n=72) following the March/April and July 2018 tephra falls (Table 4.4). Of those buildings with partial or complete roof collapse, 83% were of traditional construction (Table 4.4). Building damage was distributed widely across Ambae from the multiple tephra falls each with varying dispersal directions (Figure 4.4). On a village scale building damage also varied and was influenced by building typology and the intensity of tephra fall. Figure 4.4 shows the distribution of building damage recorded in the photographic surveys across Ambae as well as at a village scale. The villages identified in Figure 4.4 are the same as those in Figure 4.2 to highlight how building typology influenced the damage buildings sustained. Red Cliffs village was exposed to approximately 215 mm of tephra from the March/April 2018 tephra falls and had near equal proportions of traditional, non-traditional and hybrid buildings within the village. Lovunimbanga village was exposed to approximately 170 mm of tephra from the July 2018 tephra falls, but a large proportion (78%) of the buildings in the village were of traditional construction. Despite being exposed to a thinner tephra deposit, 56% of buildings sustained roof collapse (DS 4-5) in Lovunimbanga village, compared to the 16% of buildings that suffered roof collapse in Red Cliffs village This clearly highlights how building construction influenced building vulnerability to tephra fall.

Table 4.4 Building damage distribution by construction category

Construction classification		**Damage State**					
		D0	D1	D2	D3	D4	D5
Traditional	Short span	92	73	19	9	5	54
	Outhouse	3	1				
Hybrid	Modern wall, traditional roof	5	2				1
	Traditional wall, modern roof	10	1	2	2		6
	Mixed wall construction	47	13	9	3	1	3
Non-traditional	Reinforced breeze block frame	132	26	2	1	1	
	Timber frame	33	9	2	2		1
	Reinforced concrete pillars	4	2				
Temporary		10	2	1			
	Total	336	129	35	17	7	65

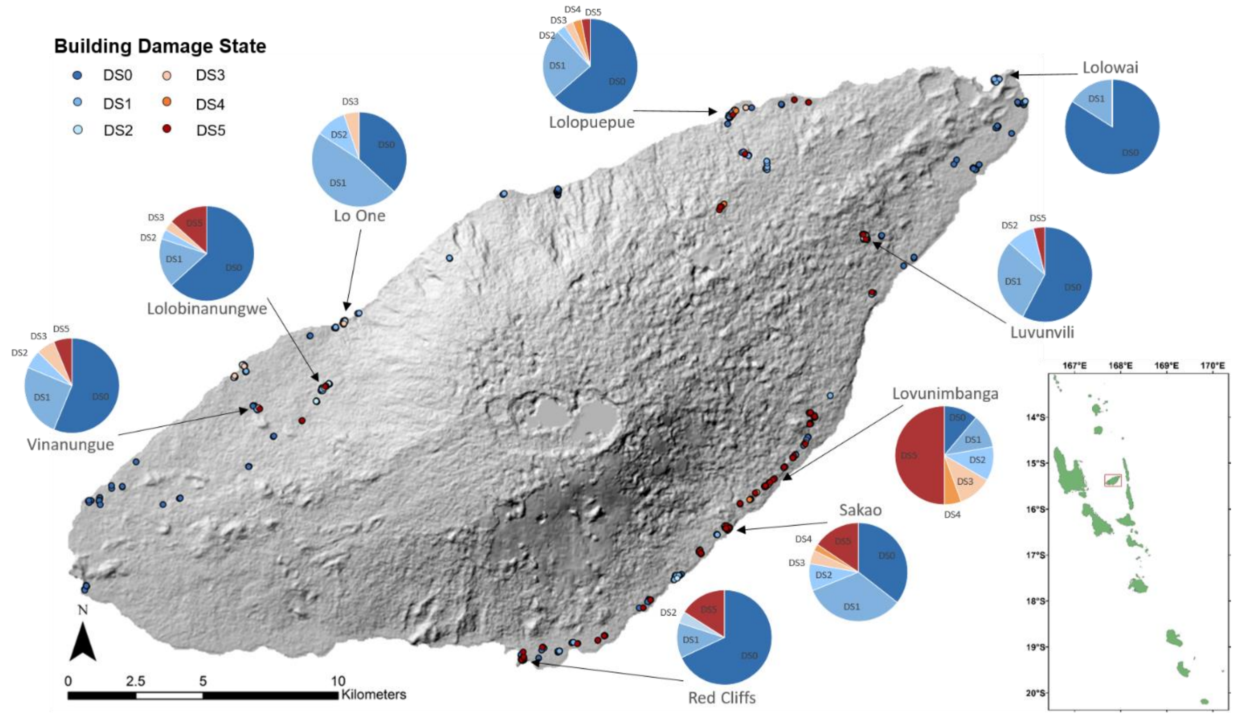

Figure 4.4 Distribution of building damage across Ambae and in specific villages that had all buildings recorded in the two photographic surveys.

Blong (2003) recorded a positive relationship between increased hazard intensity (ash loading) and increased level of building damage at Rabaul. This relationship is also evident in other building fragility curve studies (e.g. Pomonis et al., 1999; Jenkins et al., 2014; Maqsood et al., 2014). Hybrid buildings did show a weak relationship between increasing tephra thickness and building damage (Figure 4.10). However, traditional and non-traditional buildings sampled on Ambae did not show a clear relationship between increasing tephra thickness and building damage (Figure 4.5 and Figure 4.8). This suggests there were other building characteristics, not captured in the photographic survey, which contributed to the distribution of damage. As highlighted by Blong (2003) the threshold at which a building collapsed, or sustains damage may be lower than what was recorded in the field (as tephra may have continued to accumulate after collapse had occurred). However, there was insufficient time in the field to measure the tephra deposit on each building to determine the threshold at which it collapsed or sustained damage.

4.3.2.2 Traditional building damage

Traditional buildings were observed to be the most vulnerable building construction typology present on Ambae. Of the surveyed buildings that sustained any damage from tephra fall (DS1-5) 65% (n=163) were traditional buildings, and of the 65 DS5 buildings, 54 (83%) were traditional. The lowest threshold observed to generate partial (DS4) and complete (DS5) collapse in a traditional roof structure was 32 mm and 38 mm of tephra, respectively (Figure 4.5). Despite this low threshold, traditional buildings were observed to have sustained no damage (DS0) when exposed to tephra thicknesses in excess of 200 mm (Figure 4.5). This further reinforces the idea that there is a building characteristic unable captured in the photographic survey that is contributing to a traditional building's vulnerability from tephra fall. This is shown in Figure 4.6 where there are two comparable traditional buildings next to each other, but one has completely collapsed (DS5) while the other shows no evidence of any damage from tephra fall.

Traditional buildings that sustained partial collapse of the roof and supports (DS4) were rarely observed on Ambae. This was attributed to the average size and shape of traditional buildings on Ambae and the building failure methods (Section 6.2). Because the average traditional building is a short, rectangular shape, any substantial damage to the vertical load-bearing props at the edge or apex line of the roof or the primary beam at the roof apex typically resulted in collapse to more than half of the floor area of the building (DS5) (Figure 4.7).

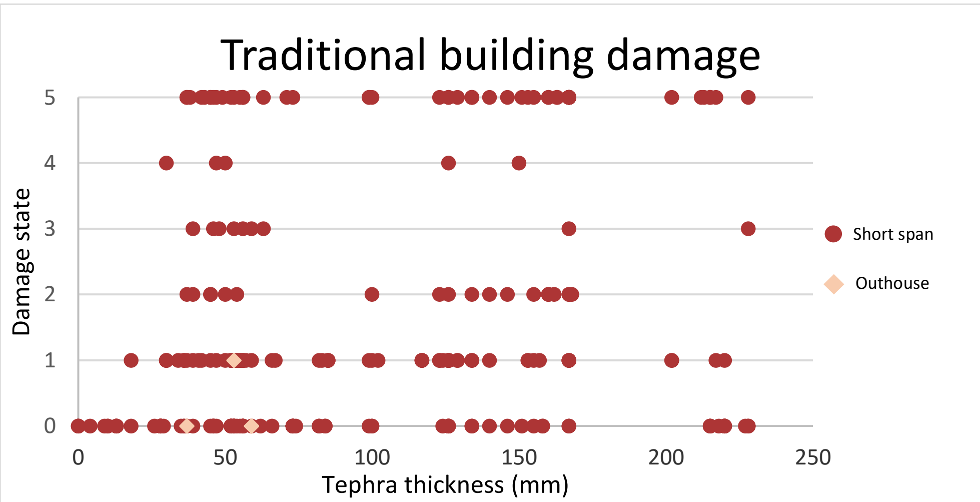

Figure 4.5 Traditional building damage distribution on Ambae, Vanuatu

Two traditional buildings with comparable construction characteristics

Left building shows no damage (DS0)

Right building sustained complete collapse (DS5) from tephra fall.

Figure 4.6 Two comparable traditional buildings that sustained different extents of damage from tephra fall

Failure in the apex beam resulting in roof collapse over more than 50% of the floor area of the building (DS5).

Figure 4.7 Traditional building that failed along the apex beam, immediately resulting in roof collapse over more than 50% of the floor area

4.3.2.3 Non-traditional building damage

The most common damage non-traditional buildings sustained was gutter collapse or failure of the corrugated sheet metal roof covers. Of the non-traditional buildings surveyed, only 20% showed signs of damage (DS1-5) following the March/April and July 2018 tephra falls. Of the 20% that sustained damage from tephra fall, 78% (n=33) had minor, non-structural damage (DS1) (Table 4.4) with approximately three-quarters (n=24) only exhibiting damage to gutters alone. Like the damage distribution for traditional buildings, non-traditional building damage distribution shows buildings exposed to large tephra thicknesses with no evidence of damage, but also buildings that exhibit structural damage at much smaller tephra thicknesses (Figure 4.8). Some non-traditional buildings that sustained structural damage at thinner tephra thicknesses showed evidence of a poor pre-eruption condition with signs of termite damage and/or corroded corrugated sheet metal (Figure 4.9).

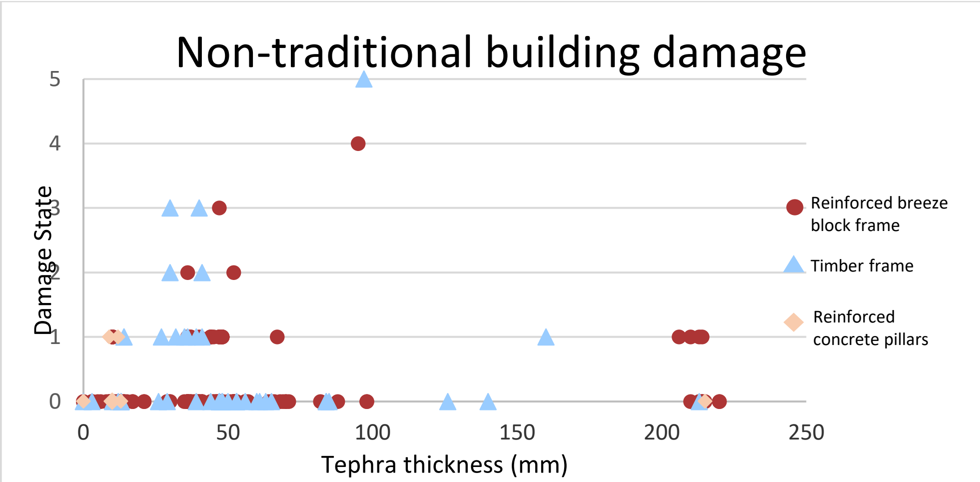

Figure 4.8 Non-traditional building damage distribution on Ambae, Vanuatu

Figure 4.9 Non-traditional building exhibiting a poor pre-eruption condition with termite damage and corroded sheet metal roof increasing the building's vulnerability to tephra fall and resulting in severe damage from 30 mm of tephra fall

4.3.2.4 Hybrid building damage

Of the hybrid buildings surveyed, 60% showed no damage following the March/April and July 2018 tephra falls of Manaro Voui. The relationship between thickness of tephra fall and building damage shows a slightly stronger correlation for hybrid buildings compared to traditional and non-traditional buildings (Figure 4.10). However, there remains a number of buildings with hybrid construction that defy expected trends, exhibiting no damage at tephra thicknesses >200 mm or roof collapse at <100 mm of tephra (Figure 4.10). Buildings which sustained damage at thin tephra thicknesses can be attributed to a poor pre-eruption condition, e.g. termite damage, brittle aged thatch or corroded corrugated sheet metal (Figure 4.11). Hybrid buildings that had more traditional construction features were also observed to sustain more damage than buildings with less traditional construction features (Figure 4.11). This reinforces the idea that traditional buildings are more vulnerable to tephra loading than non-traditional buildings.

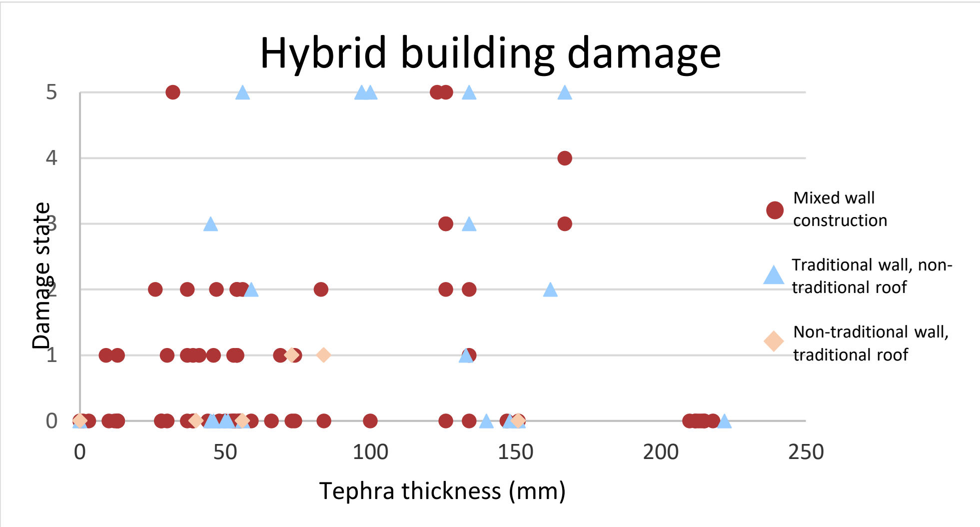

Figure 4.10 Hybrid building damage distribution on Ambae, Vanuatu

Traditional thatch roof framed with bamboo sustaining roof collapse at ~47 mm of tephra.

Traditional thatch roof framed with sawn timber sustaining no damage at ~47 mm of tephra.

Hybrid building in a poor pre-eruption condition with the corroded corrugated sheet metal roof failing at ~40 mm of tephra.

Hybrid building where the traditional construction features have failed from ~123 mm of tephra.

Non-traditional construction features show very little damage.

Figure 4.11 Examples of the damage hybrid buildings sustained from tephra fall on Ambae and how their construction or condition influenced the damage they sustained

4.3.2.5 Longitudinal damage

Two villages visited both during the first and third field visit had buildings that increased in damage state between each visit. The first, Building ID 43, is a traditional building located in Lolombinanungwa village, West Ambae. This building showed no signs of damage (DS0) after being exposed to 53 mm of tephra during the March/April 2018 eruption phase. Figure 4.12a shows that the bulk of the tephra was removed (by human or environmental actions) from the roof following the March/April 2018 tephra falls. Following a further 38 mm of tephra from the July 2018 tephra falls, the same building had completely collapsed (DS5), representing the lowest recorded threshold for complete collapse of a traditional building on Ambae (Figure 4.12). From available photographs, the primary beam and rafters of the building had failed though the order of which cannot be determined.

Figure 4.12 Longitudinal building damage observed in Lolombinanungwa village, West Ambae. (a) Building ID 43 after 53 mm of tephra during the March/April 2018 tephra falls. (b) The same building following a further 38 mm of tephra during the July 2018 tephra falls.

Red Cliffs village, South Ambae experienced approximately 215 mm of tephra following the March/April 2018 tephra falls, followed by 20-30 mm of tephra during the July 2018 tephra falls. Building ID 04 is a hybrid building and sustained no damage after the March/April 2018 tephra falls (Figure 4.13a). By the third field visit in August, after an additional 25 mm of tephra fall during the July 2018 tephra falls, the building sustained damage to the already heavily corroded corrugated sheet metal roof. Large holes had formed in the roof above areas not supported by rafters or trusses (Figure 4.13b). Similar damage mechanisms were observed in other buildings (e.g. Figure 4.9). It is suggested that the failure of the corroded corrugated sheet metal roofs was caused by tephra loading. However, it is the poor condition of the roof, caused by prolonged exposure to the tropical environment and acid rain generated by Manaro Voui that would have corroded the roof to a point, where once a load was applied, it failed in places not supported by rafters or purlins beneath.

Figure 4.13 Longitudinal building damage observed in Red Cliffs, South Ambae. (a) Building ID 04 after 215mm of tephra during the March/April 2018 tephra falls. (b) The same building following a further 26mm of tephra during the July 2018 tephra falls.

4.3.2.6 Building Failure Methods

Of the buildings that suffered collapse (DS5; n=66), the majority (n=48) were traditional short-span buildings (Ts). There were two main modes of failure for this building type:

1. Failure of the vertical load-bearing props at the edge or apex line of the roof (Figure 4.14)
2. Failure of the primary beam (at the roof apex: Figure 4.15)

There were also buildings where the rafters had failed, but it was often not clear if rafter failure preceded or followed different modes of failure, e.g. Figure 4.16 where there was also primary beam failure in in the adjoining part of the building structure.

In a small number of buildings, building damage was likely exacerbated by termite damage in the timber support structure of the roof. 'Slipping' of the timber thatch down-pitch along the rafters and away from the primary beam was observed. This likely reflects a poor connection between the thatch and primary beam, or a support structure that could resist more vertical loading than the grip of the connection (vine ties) could, meaning the ties could slip down-rafter or snap.

Figure 4.14 Complete collapse of an open-sided traditional building, where the vertical load-bearing props (tree trunks) snapped at their base. (55 mm)

Figure 4.15 Roof collapse of an open-sided traditional building where the primary beam broke, but the vertical load-bearing props remain intact. (53 mm)

Figure 4.16 Roof collapse of a traditional building, where the vertical load-bearing props and apex beam remain intact (in the front section), but the principal rafters are detached and damaged. (134 mm)

For corrugated sheet metal roofs, damage differed according to the condition and likely age of the roof. For poor condition and corroded sheet metal roofs, failure was typically through the roof covering, with the roof support structure remaining intact. Good condition sheet metal roofs showing no corrosion, exhibited collapse of the roof and support structure with destabilisation of the walls. Failure of the roof support or load-bearing structure, rather than the roof covering, was observed, although it was difficult to see which component/s had failed. For sheet metal roofs in average condition with some corrosion, flexing of the sheets and rafters under the tephra load was observed. In some buildings, the rafters had started to fail but had not given way completely.

4.3.2.7 Non-structural damage

Gutter damage was the most common form of damage to non-structural elements (DS1) observed on Ambae. Gutters are only found on buildings with corrugated sheet metal roofs, though not all corrugated sheet metal roofs necessarily had gutters. Gutters represent an important, yet vulnerable feature of buildings on Ambae. Rainwater-fed tanks and wells which frequently rely on gutters are the primary source of drinking water for 88% of residents on Ambae (VNSO, 2016). Therefore, any loss of gutter functionality can affect water supply and impact the habitability of an area. This is even more important for isolated communities that may not have the resources to quickly repair or replace damaged gutters. Building ID 114 represents the lowest threshold for gutter damage with approximately 9 mm of tephra from the March/April 2018 tephra falls (Figure 4.17). Despite being exposed to a thin tephra thickness, the damage to the gutter was from the accumulation of tephra on the roof's large surface area which captured a sufficient volume of tephra to overload the gutters.

Figure 4.17 Building ID 114 represents the lowest threshold of tephra fall causing gutter damage with 9 mm. This low threshold is attributed to the large surface area of the roof being able to collect a greater volume of tephra.

4.4 BUILDING MITIGATION METHODS

The following section evaluates the effectiveness of observed building mitigation techniques that minimised the impact buildings sustained from tephra fall, both in terms of building damage and disruption, achieving this thesis' fifth objective;

- *Objective 5: Evaluate the effectiveness of mitigation techniques used by Ambae residents to minimise the impact buildings sustained from tephra fall and assess suitability of these methods for future eruptions in other areas exposed to tephra fall.*

A range of mitigation methods were undertaken by residents of Ambae to minimise the impact of tephra fall on buildings. These included covering roofs with tarpaulins, reinforcing the roof support structure, removing gutters, clearing tephra off roofs and covering building openings. The following section describes each mitigation method. Where applicable, an evaluation of the overall effectiveness of the mitigation method in reducing building damage from tephra fall is provided.

4.4.1 Tarpaulin roof covers

Tarpaulins were installed on the roofs of 47 buildings surveyed, 91% of which were traditional thatch roofs. The textured surface of traditional thatch retained tephra well compared to corrugated sheet metal roofs. Traditional thatch roofs, which had been cleared of tephra by people or other means of removal still had tephra lodged between individual fronds of the thatch roof. Tarpaulins which adapted the thatch roof surface, generated a smoother roof surface, reducing the surface friction and allowing tephra to shed more easily. This was observed on Building ID 448 (Figure 4.18) where the portion of the roof covered with a tarpaulin had shed most of its tephra, but the portion of the roof that had not been covered with a tarpaulin retained tephra.

Figure 4.18 Ambae building with a traditional thatch roof, partially covered with a tarpaulin. The portion of the roof covered with the tarpaulin has already shed most of the tephra, whilst the portion of the roof with no tarpaulin continues to retain tephra.

Most traditional buildings that had been installed with tarpaulins were observed in South Ambae (Table 4.5). Of the 171 traditional buildings surveyed in South Ambae, 21% (n=36) had a tarpaulin installed over the thatch roof (Table 4.5). Buildings in South Ambae installed with tarpaulins had a smaller proportion (14% n=5) of structural roof damage (DS=4-5) than traditional buildings without tarpaulins (32%, n=44) (Figure 4.19). Traditional buildings in South Ambae with tarpaulins also had a noticeably larger proportion of no or minor non-structural damage (DS=0-1) than those with no tarpaulins (Figure 4.19). The proportion of traditional buildings with no damage is larger for buildings with tarpaulins installed (36%, n=13) than buildings without tarpaulins (25%, n=34). It is therefore inferred that the larger proportion of minor damage (DS=1) in traditional buildings with tarpaulins (44%, n=16) is the result of the roofs being able to shed tephra more easily reducing the tephra load on a building structure, minimising the building's vulnerability and preventing severe structural damage.

The effectiveness of installing a tarpaulin over a traditional thatch roof surface to reduce the damage from tephra fall suggests that traditional thatch roofs are vulnerable characteristics of traditional buildings. Tarpaulins effectively reduce the friction on the roof surface allowing the tephra to shed. They are a cheap, cost effective mitigation method that can be easily installed over roofs and are commonly gifted as foreign aid during crises like the Manaro Voui volcanic crisis. It is therefore recommended that the installation of tarpaulins over thatch roof surfaces be implemented as a mitigation method to minimise traditional building damage in future volcanic eruptions and further work go into investigating the potential application of tarpaulins on other roof surfaces.

Table 4.5 Distribution of traditional buildings with and without roof surface adaptation mitigation methods recorded in Ambae

	Traditional buildings	
	No tarpaulin installed	**Tarpaulin installed**
North Ambae	19	0
East Ambae	25	2
West Ambae	39	2
South Ambae	135	36

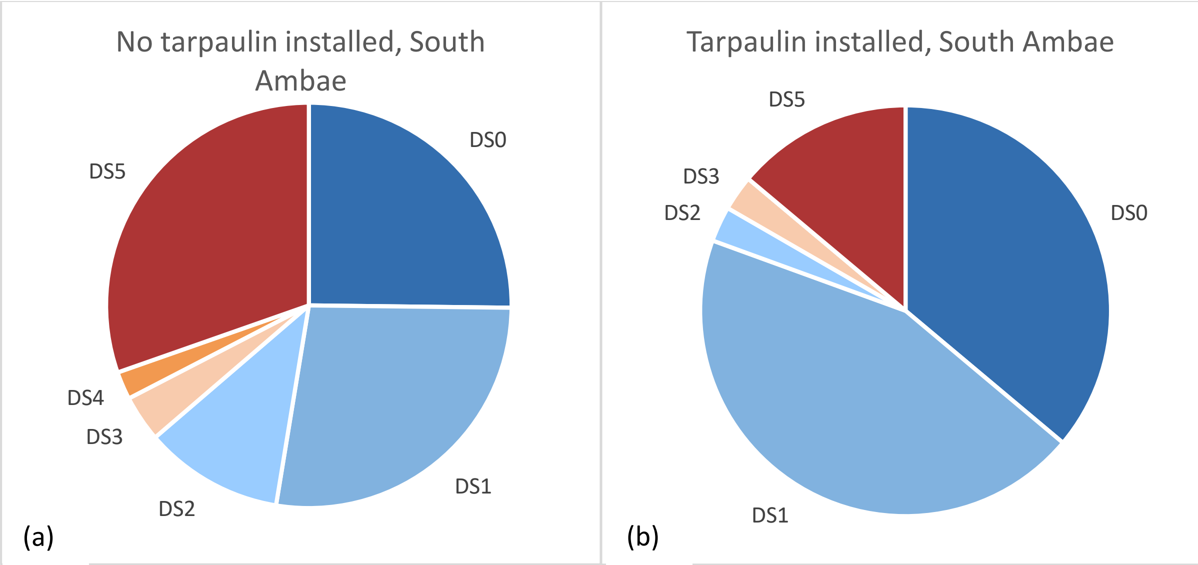

Figure 4.19 Distribution of the damage traditional buildings sustained in South Ambae (a) Traditional buildings with no tarpaulin installed on the roof (b) Traditional buildings with tarpaulins installed on the roof.

4.4.2 Removal of gutters

Of the 589 buildings surveyed on Ambae, 58 had gutters, with a further 35 buildings showing evidence of having had gutters removed. Of the 58 buildings with gutters, 38 (66%) sustained damage from tephra fall, 34 of which had damage that was solely attributed to gutter damage alone. It is recognised that the amount of gutter damage may be more than what is recorded in the building inventory as there were buildings observed that had evidence of once having had gutters (i.e. brackets or hangers remained on the roof eaves) but the gutters themselves had been removed and could not be seen. The circumstances under which some gutters were removed was not always identifiable in survey photographs and gutters may have been removed because of damage rather than pre-emptively as a method to minimise contamination of water sources. There are some circumstances where it is known that gutters were pre-emptively removed to minimise contamination of water supplies and to prevent damage in the event of an eruption (Figure 4.20). Regardless of the circumstances in which gutters had been removed, their removal could had potentially mitigated a substantial amount of building damage and helped prevent tephra contamination of drinking water sources.

Figure 4.20 Roof structure that shelters a water tank had its gutters removed during tephra fall so that tephra could not contaminate the drinking water source and subsequently prevented gutter damage from tephra loading.

Whether or not the removal of gutters can be used as an effective form of building mitigation from tephra fall would need to be evaluated on a case by case basis. Factors that would need to be considered when determining if gutter removal is an effective mitigation technique are as follows:

- Whether or not there are adequate resources for gutters to be removed and later re-installed safely to minimise personal injury.
- The number of buildings with gutters that would have to be removed.
- Whether there is sufficient time for people to safely remove gutters before tephra begins to fall.
- Whether there are other advantages for removing gutters e.g. preventing tephra entering and contaminating drinking water supplies.
- Whether certain buildings be prioritised such as schools and hospitals as these facilities often play a crucial role during a disaster response.

On Ambae it may have been worth removing guttering systems from buildings. Not only does this prevent gutter damage from tephra loading, but it also stops tephra from being able to enter and contaminate the primary drinking water supply for residents.

4.4.3 Reinforcement of roof support structure

Reinforcement of the roof support structure was observed in both traditional and hybrid construction building typologies with the installation of an additional pole supporting primary beams from the floor. This mitigation technique was only observed in two buildings surveyed as the photographic survey methodology meant that most buildings were not entered. This creates an additional source of uncertainty in the building inventory, as reinforcement of the roof support structure may be a reason why some buildings performed better than expected under tephra loading. Building ID 258 (Figure 4.21a) is a hybrid building that was exposed to approximately 126 mm of tephra during the July 2018 tephra falls. There was extensive bending of the corrugated sheet metal roof and the primary rafters and purlins had snapped (Figure 4.21b), but none of the roof structure had collapsed. In the centre of the building was a pole propping the roof from the floor, providing additional support. The pole appeared out of place in the building and was inferred to have been installed in response to the tephra loading of the roof structure (Figure 4.21c). Given the damage the rafters and purlins in the roof structure sustained from tephra loading the pole likely prevented the roof structure from collapsing.

4.4.4 Roof clearing

Roof cleaning techniques varied depending on whether the roof cover was traditional thatch or corrugated sheet metal. In addition to brooms which were used to clear tephra from corrugated sheet metal roofs, plastic half pipes, lengths of gutters and homemade rakes with corrugation patterns (Figure 4.22) were all used by Ambae residents to help remove tephra from the troughs of corrugated sheet metal. Traditional thatch roofs were either cleared of tephra from the ground with long handled brooms, by children who could climb on the roofs with brooms and rakes, or no action was taken and passive tephra removal was left to the rain and wind.

Figure 4.21 Building ID 258 exposed to approximately 126 mm of tephra during the July 2018 eruption phase. (a) exterior of the building with visible bending in the corrugated sheet metal roof cover. (b) Purlin beam which had snapped from the tephra loading and bending roof cover. (c) Pole installed to reinforce the roof support structure along with extensive bending in the roof cover and support. (Photo credit Susanna Jenkins)

Figure 4.22 Innovative methods used to clear tephra off roofs on Ambae. (a) Plastic half pipe. (b) Length of guttering. (c) Homemade rake with inbuilt corrugation pattern.

4.4.5 Building interior contamination mitigation

The reduced habitability on Ambae was the primary motive for evacuation following the July 2018 tephra falls. Buildings had collapsed, crops were damaged, limited drinking water resources had been contaminated by tephra and dry season trade winds were reworking tephra and recontaminating buildings. Even buildings not damaged by tephra were impacted due to tephra ingress indoors. Non-traditional buildings on Ambae, like many non-air conditioned buildings in tropical environments, are not fully sealed and have a gap between the external wall and roof (Figure 4.23a). This gap is a passive form of cooling, promoting turbulent air flow up the exterior of the building and allowing convective air flow through the building, which is essential for buildings in tropical environments. However, this passive form of cooling provides a pathway for tephra suspended in the turbulent airflow to enter buildings and contaminate the building interior (Figure 4.23b). Non-traditional buildings on Ambae also have windows to promote convective air flow and were most commonly installed with glass louvers. Windows enabled tephra suspended in turbulent air to enter a building, and it was observed that window louvers were regularly coated in tephra.

Traditional buildings are also vulnerable to tephra contamination in building interiors. Nakamals, (traditional meeting places) and cooking houses regularly lack cladding on portions of external walls (Figure 4.23c). External walls with no cladding on traditional cooking houses are crucial for ventilation so that smoke from cooking fires can easily exit the building (Coiffier, 1988), however this also makes it easier for tephra to enter buildings without portions of external wall cladding. Traditional buildings completely enclosed by external wall cladding (usually split bamboo) still allow tephra to enter the building interior through the traditional thatch roof and split bamboo cladding materials.

Figure 4.23 Characteristics of Ambae buildings which make them vulnerable to tephra ingress reducing their habitability. (a) School building, Lovunivili village, East Ambae with a gap between the external wall and roof structure, and louver windows. (b) Interior of the school building with a thick tephra deposit inside from ingress. (c) Traditional Nakamal with exposed openings at either end of the building which allowed tephra into the building during the July 2018 tephra falls.

4.4.6 Tephra contamination mitigation

Attempts to mitigate tephra contamination in buildings mostly involved covering building openings. Tarpaulins were observed covering external openings of traditional buildings to minimise airflow carrying tephra through them (Figure 4.24). Tarpaulins installed over thatch roofs were also reported to reduce tephra's ability to ingress through the thatch cover. Window openings of non-traditional buildings were covered with tarpaulins or cloth to minimise airflow pathways into the buildings (Figure 4.24) but covering the gap between the external wall and roof of non-traditional buildings was not observed. Other attempts to minimise tephra contamination in buildings also included attempts to reduce remobilisation by wind or foot traffic. For example, in Lolopuepue village, coconut leaves were observed scattered over a zone of barren, tephra-coated land in an area of high foot traffic.

Despite best efforts to prevent tephra contaminating building interiors, mitigation techniques only minimised tephra ingress, with traces of tephra inevitably coating interior surfaces. Covering openings did minimise tephra ingress, but tephra was still easily transferred into buildings by people entering as it adhered to feet and clothing. Using fabric to cover openings was not as effective as tarpaulins in minimising tephra ingress. In order to be effective, all openings need to be covered, and ideally installed proactively before tephra begins to fall and remain in place until the tephra is no longer being remobilised. This is made difficult by the need for circulation in non-traditional buildings to keep cool, and ventilation in traditional cooking houses to remove the smoke of cooking fires.

Figure 4.24 Mitigation techniques observed in Ambae for minimising tephra contamination in buildings. (a) covering on large openings on traditional buildings (b and c) covering of small window openings (d) coconut leaves scattered over an area of barren tephra-coated land with high foot traffic.

4.5 SUMMARY

Chapter Four presented the methodology that was used to take a photographic survey of buildings and develop a comprehensive record of the damage tephra fall caused to buildings on Ambae. The results from this record of building damage from tephra fall were analysed to determine building and environmental characteristics that made buildings in Ambae vulnerable to tephra fall. Finally, based on observations made in the field building mitigation methods were evaluated based on their effectiveness of minimising impacts on the habitability of buildings. Thus, Chapter Four has achieved the following objectives;

- *Objective 3: Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*
- *Objective 4: Analyse the impact of tephra fall on buildings in Ambae and how construction characteristics or environmental factors may have influenced individual building vulnerabilities to tephra fall.*
- *Objective 5: Evaluate the effectiveness of mitigation techniques used by Ambae residents to minimise the impact buildings sustained from tephra fall and assess suitability of these methods for future eruptions in other areas exposed to tephra fall.*

CHAPTER FIVE: CONCLUSIONS

Chapter Five concludes the thesis by presenting how the objectives outlined in Chapter One were achieved and the key findings from each objective. A reflection on the methodologies developed and used to achieve the thesis' aims is also provided, together with potential research opportunities that could be further developed from the work achieved in this thesis.

The 2017/18 eruption period of Manaro Voui had two periods of tephra falls (March/April and July 2018) that impacted exposed buildings on Ambae. The aims of this thesis was to record the impact of the March/April and July 2018 tephra falls on buildings in Ambae, and develop an understanding of the vulnerability of traditional Pacific Island buildings to tephra fall. Five objectives outlined in Chapter One were set out to achieve the thesis's aims and are detailed below:

Objective 1: *Establish the risk context of the volcanic crisis for the Island of Ambae 2017/18 with a focus on the built environment*

A literature review presented the risk context on Ambae during the 2017/18 volcanic crisis in terms of the tephra fall hazard, assets on Ambae exposed to tephra fall, and the known inherent vulnerabilities of those assets. Key findings from the literature review are as follows:

- Ambae has an isolated and vulnerable population of 10,858 people prior to the 2017/18 volcanic crisis. Traditional buildings make up 51% of their residential buildings and they are reliant on the success of their crops both as a source of food and for income. Primary drinking water for 88% of the population is sourced from rainwater-fed tanks and wells.
- Manaro Voui volcano has a history of producing tephra falls. The 2017/18 eruption period produced a series of complex and intermittent tephra falls that impacted the built environment.

- The processes that form and disperses tephra fall are well understood, but the impact of tephra fall on buildings is not as well understood. This is particularly relevant to the traditional buildings in Ambae because of their construction from locally-sourced materials.
- There is no record of the impact of tephra falls on traditional buildings in the literature and the vulnerability model that exist for traditional buildings are based on expert judgement. There is also no record on how tephra fall disrupts the functionality of a building without causing any damage, or how building impacts change over a prolonged or complex multi-phased eruption.
- Drawing from studies that recorded the impact of past tephra falls on buildings, photographs and descriptions of the damage buildings sustained from tephra fall have been utilised effectively. Rather than record a GPS location for each building visited with a description of the damage whilst in the field, a methodology was proposed that used the GPS locations attached to photographs when taken and satellite imagery to locate buildings. This methodology would prove to significantly reduce the time required in field and allowed a greater breadth of coverage across Ambae.

Objective 2: *Develop tephra fall hazard models for the March/April and July 2018 tephra falls of Manaro Voui volcano.*

An overview of Manaro Voui's 2017/18 eruption chronology was compiled, highlighting the complexity of the intermittent tephra falls during the prolonged eruption period. Although there were multiple tephra falls, only five tephra falls were reported as having caused damage to buildings on Ambae; three during March/April 2018 and two during July 2018.

Using measurements of the tephra deposit thickness collected during three post-eruption field visits, two tephra fall hazard models were developed to represent the March/April and July 2018 tephra falls of Manaro Voui in the form of an isopach map. The March/April 2018 tephra fall hazard model consisted of three tephra falls that occurred on the 15-16th and 21st March and 9-11th April. The July 2018 tephra fall hazard model consisted of two tephra falls that occurred on the 1st and 16-25th July.

Objective 3: *Collect a comprehensive record of the damage Ambae buildings sustained during the March/April and July 2018 tephra falls of Manaro Voui volcano.*

A methodology was developed that used photographic surveys in the field to rapidly capture the damage buildings on Ambae sustained from tephra fall and satellite imagery to locate buildings identified in the photographs. From this a comprehensive record of the damage buildings sustained from the March/April and July 2018 tephra falls of Manaro Voui was established. This thesis successfully recorded the locations and construction characteristics of 589 buildings captured in the photographic surveys taken on Ambae.

The damage buildings sustained from tephra fall was described according to a 'damage state' framework, developed for this thesis. The damage state framework developed drew from previous frameworks used in previous studies, but was tailored so that the damage criteria was suitable for the building typologies present on Ambae. Changes made are those that suit building typologies in developing, subsistence populations in tropical environments: these included removing damage to air conditioning units, electrical systems and tile roofs as these are typically not present in areas such as Ambae.

Objective 4: *Analyse the impact of tephra fall on buildings in Ambae and how construction characteristics or environmental factors may have influenced individual building vulnerabilities to tephra fall.*

The record of the 589 buildings damaged on Ambae from the March/April and July 2018 tephra falls were analysed in terms of the distribution of damage, the influence of construction typologies on the extent of damage and the building failure mechanisms that were identified. From this damage record the following observations were made:

- The lowest observed thickness of tephra fall causing roof collapse (DS5) was 38 mm for traditional buildings, 97 mm for buildings of non-traditional construction, and 32 mm for buildings with a hybrid construction.
- Despite low thresholds of tephra fall generating collapse, some permanent buildings of each typology sustained no damage in areas exposed to tephra fall >200mm.
- Poor pre-eruption conditions such as termite damage or corroded corrugated sheet metal roofs contributed to building damage at low tephra fall hazard intensities in hybrid and non-traditional buildings.
- Two primary modes of building collapse were observed in traditional buildings, these being failure of the vertical load-bearing props at the edge or apex line of the roof, and failure along the primary beam in the roof apex.
- Non-structural damage to gutter systems was commonly observed on non-traditional buildings. Of the 58 non-traditional buildings recorded as having gutters, 34 (59%) sustained damage solely to their gutter systems due to tephra fall.

From the results of the building inventory it is concluded that traditional buildings are more vulnerable to tephra fall from loading. For the 44 hybrid and non-traditional buildings that sustained damage at low tephra fall intensities (<50 mm), there was usually evidence of either poor pre-eruption condition (e.g. termite damage or corroded sheet metal roofs), or the damage was associated with weak or non-structural elements (e.g. gutters or overhangs). This was not always the case for traditional buildings, with no evidence to suggest why many sustained substantial damage at low tephra fall hazard intensities.

It was noted from the results that there was not a clear positive relationship between increasing hazard intensity and increased level of building damage, particularly for traditional and hybrid construction buildings. This leads to the conclusion that there may be another characteristic of these buildings, beyond basic construction materials and design that is causing the observed building damage distribution. It is therefore important that future work on traditional building vulnerability to tephra fall considers what other factors (e.g. building age, construction material quality, pre-eruption condition, unreinforced roof support structure) may cause a traditional building to sustain damage from tephra fall.

Objective 5: *Evaluate the effectiveness of mitigation techniques used by Ambae residents to minimise the impact buildings sustained from tephra fall and assess suitability of these methods for future eruptions in other areas exposed to tephra fall.*

The implementation of any building mitigation methods for reducing the impact of tephra fall on buildings was also analysed. Evaluating the effectiveness of these mitigation methods involved both analysing the record of building damage developed for this thesis, and also observations made by the field teams and reports from Ambae locals. From the analysis of the building mitigation methods, the following conclusions were made:

- Tarpaulins over traditional thatch roofs showed clear evidence of being effective in minimising building damage from the tephra loading by reducing friction and allowing tephra to shed off the roof surface more easily.
- Pre-emptive removal of gutters was shown to be an effective method for not only minimising building damage, but also by limiting the ability for tephra to enter and contaminate primary drinking water supplies. It is stressed, however, that the effectiveness of removing gutters as a method for mitigating building damage must be evaluated on a case by case basis, and may not be appropriate in all volcanic crises involving tephra fall.
- The use of poles to reinforce the roof support structure was only observed in two buildings. For one of these buildings, given the extent of damage to rafters and purlins it was inferred that the roof structure did not collapse because of the pole that was installed to provide additional support to the roof system. This suggests that for appropriate designed and

constructed buildings, props could be installed (either in a permanent or temporary capacity) to reduce building vulnerability to tephra loading on the roof structure.

- Methods to keep tephra out of buildings and maintain the building's habitability were observed, but the construction of many buildings promotes passive cooling and this made maintaining an environment that prevented tephra ingress into buildings challenging.

The effectiveness of these building mitigation techniques provide an insight into the vulnerability of buildings on Ambae. If a mitigation technique is effective it suggests that the building characteristic that is being adapted or changed is vulnerable. The installation of tarpaulins over traditional thatch roofs was the only building mitigation technique observed that had enough evidence to suggest its effectiveness as a viable technique for minimising the vulnerability of traditional buildings to tephra fall. Other observed mitigation options could still be viable options for reducing a building's vulnerability, but more assessment is required to validate their effectiveness as building mitigation methods from tephra fall hazards.

5.2 REFLECTION ON THESIS METHODOLOGY AND LIMITATIONS

5.2.1 Methodology reflection

The following section reflects upon the methodologies developed as a part of this thesis and identifies the methodology limitations and how it may be improved in future projects. Each field visit to Ambae was limited not only by time but also accessibility to certain parts of the island. Data collection on Ambae to develop the March/April and July 2018 tephra fall hazard models and record building damage was rapid and at a lower level of detail than is ideal. Because empirical data on how tephra fall impacts buildings is scarce, it was important this thesis developed a methodology that was able to effectively utilise this rare dataset.

5.2.1.1 Tephra fall hazard model development methodology

The methodology used to develop the March/April and July 2018 tephra fall hazard models for Manaro Voui used in-field measurements of the tephra deposit thickness at known locations. All three field visits to Ambae occurred during a dynamic and developing volcanic crisis. Logistics were challenging as depleted resources such as vehicles and fuel were prioritised for the residents of Ambae. Tephra fall and lahars made it challenging to access some areas of Ambae but field visits were planned in such a way to maximise coverage during the time available. Gaps were present between tephra deposit measurements sites, but these gaps were supplemented with alternative data sources. Alternative sources of data which estimated the tephra deposit thickness came from field photos, field team and local resident estimates, with each ranked based upon their expected representation of the tephra deposit.

Time constraints during each field visit meant that for most locations visited only measurements of the tephra deposit thickness was able to be taken. This limited the amount of tephra bulk density measurements available to develop a robust tephra fall hazard model that could relate tephra loading to building damage. The locations where the density of the tephra was measured (either in field or in a lab) showed great variability in bulk density and contained greater gaps spatially around Ambae than the tephra thickness measurements. Therefore, it was decided that the tephra fall hazard model would use the thickness of the tephra deposit to relate to the damage buildings sustained from tephra fall on Ambae, rather than tephra loading. This decision was made based on the data that was able to be collected while in the field and could be used to produce hazard models that best represented the March/April and July 2018 tephra falls of Manaro Voui.

Future studies would benefit from a method that allows for rapid in-field measurement of tephra density in addition to tephra deposit thickness or a method that does not rely on detailed field work. With recent advancements in remote sensing technology, there is the potential for a methodology to be developed that could estimate the thickness of a tephra fall deposit which could be later ground-truthed with a rapid field assessment of the deposit.

It is also recognised that delays between the deposition of the tephra fall and the measurement of the deposit would have resulted in compaction and erosion of the tephra deposit. Tephra deposit compaction is an unavoidable process if the deposit cannot be measured directly after its deposition. It is recognised that some of the tephra deposit measurements used to develop the tephra fall hazard models are minimum thickness values for the tephra deposit. Because volcanologists cannot always be present during tephra falls, willing residents in volcanically active areas could be trained in measuring tephra deposit thicknesses. Tephra deposit measurements taken by residents can then be used by volcanologists for the development of more robust tephra fall isopachs and hazard models.

5.2.1.2 Building inventory methodology

Photographic surveys were used to develop the building inventory for Ambae. The same photographs were then used to describe the damage buildings sustained from tephra fall using the damage state framework developed as a part of this thesis. The photographic surveys minimised the required assessment time in the field, covered a large area and produced a meaningful assessment of building damage from tephra fall. However, by developing a methodology that rapidly collected data, it would sometimes create sources of uncertainty regarding a building's location, construction characteristics or damage sustained. These sources of uncertainty came from photograph quality or the quantity of photographs taken for each building. When uncertainty in the data was identified it was recorded within the building inventory to recognise that such uncertainty existed.

A drone provides an alternative method to hand-help cameras for capturing site data rapidly and accurately. A drone taking a video could capture detailed imagery of the damage buildings sustained more efficiently, have a full 360 view of buildings, and make locating buildings on satellite imagery more efficient. The GPS tracks and geolocation tags on photos were not always accurate and sometimes the spatial relationship with buildings or features in the background of a photograph had to be used to locate some buildings on the satellite imagery. The disadvantage of using a drone is that it requires a trained operator and must be charged regularly, and access to an electricity supply was not always guaranteed during field visits on Ambae.

This methodology to survey building damage from tephra fall would also benefit from having recent satellite imagery. After the March/April 2018 tephra falls, some villages in South Ambae were permanently relocated and new villages were established in areas not yet impacted by heavy tephra fall. These new villages were recorded in the photographic survey following the July 2018 tephra falls but could not be seen in the satellite imagery that was taken before the start of the eruption phase. Recent satellite imagery would have reduced the uncertainty of locating these new villages, and it is also potentially a useful way to record population movements during a prolonged eruption period.

5.2.1.3 Summary

There were limitations to the methodologies developed as a part of this thesis to achieve its aims. Working in a dynamic, post-volcanic eruption environment is challenging. The limitations with developing tephra fall hazard models are inherent and common issues to those who have previously developed tephra fall hazard models from tephra deposits. The field visits to Ambae that collected the photographic surveys were there for humanitarian support, so a detailed impact assessment of building damage was not the primary focus of the visits. However, these field visits provided a rare opportunity to gain insight into the vulnerability of traditional Pacific buildings to tephra fall and to record empirical data necessary for developing vulnerability models used in volcanic risk assessments to inform DRM decisions. Therefore, this rapid data collection and processing method was developed, and is considered appropriate in the circumstances.

5.3 FUTURE RESEARCH

5.3.1 Vulnerability model development for traditional buildings

This study is the first empirical dataset for traditional Pacific buildings damaged by tephra fall. The importance of this empirical data for informing vulnerability models for traditional constructed buildings was highlighted in Chapter Two. For this work to be applicable to similar construction types globally, more work is needed to develop vulnerability models and help understand the relationship between traditional buildings and tephra fall hazard. The development of a vulnerability model for traditional buildings from tephra fall will still need to be supplemented with experimental and theoretical data until more extensive empirical dataset can be collected and integrated into the vulnerability model. Once a vulnerability model is developed, risk assessments can be carried out and be used to inform DRR decisions.

5.3.2 Understanding traditional building vulnerability for mitigation method development

Using the observations on the building failure methods, future work could focus on developing mitigation methods that reduce building vulnerability, and thereby minimising the damage it may sustain from tephra fall. This thesis provided evidence which suggested that installing tarpaulins over traditional thatch roofs helps mitigate building damage from tephra fall as the tarpaulin reduces the friction coefficient of the roof surface allowing tephra to shed off more easily. These results could be further developed through experimental studies that test how different roofing materials and roof design (e.g. pitch) retain tephra and confirm whether tarpaulin does cause tephra to shed from a roof more easily. Other mitigation methods such as reinforcing the roof support structure and removing gutters would also benefit from further investigation into their effectiveness at minimising damage. The benefit of reinforcing a roof support structure would need to be evaluated through experimental and theoretical studies. The effectiveness of removing gutters can be evaluated through cost benefit analysis which can include other factors which are important to consider. These considerations should include whether there are benefits to removing gutters, or whether gutters be removed and reinstalled efficiently and safely. This work can inform DRM decisions and provide information and advice on how to mitigate the impact tephra fall on both non-traditional and traditional buildings.

5.3.3 Development of rapid field data collection methods for post-impact environments

There is also the opportunity to utilise drones as a tool to assist with recording and analysing the impact tephra fall had not only on buildings, but also on other infrastructure as well as agriculture. Using a drone to collect building impact data in the field would improve the detail on the impact and make processing the data collected in the field more efficient. The potential for using remote sensing from satellite data was also investigated, however the tropical location of Ambae meant that it was often covered in cloud and most remote sensing data was not useful for the purpose of observing the impact tephra fall had on Ambae. This does not, however, mean that remote sensing cannot be used for analysing the impact of future volcanic eruptions. Remote sensing has the potential to overcome the challenges of visiting post-volcanic eruption environments, and greatly improve our pool of empirical data on volcanic hazard impacts.

References

Alloway, B.V., Lowe, D.J., Larsen, G., Shane, P.A.R., Westgate, J.A. (2013). Tephrochronology. In: Elias S.A. (ed.) *The Encyclopaedia of Quaternary Science* (vol. 4., pp. 277-304). Amsterdam: Elsevier.

Australian Humanitarian Partnership. (2017). Ambae Island volcano – Vanuatu. Retrieved from: https://www.australianhumanitarianpartnership.org/preparedness-1/ambae-island-volcano

Baxter, P.J., Horwell, C.J. 2015. Impacts of Eruptions on Human Health. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes*. (2nd ed., pp. 1035-1043. San Diego: Academic Press. DOI: http://dx.doi.org/10.1016/B978-0-12-385938-9.00060-2

Biass, S., Bonadonna, C., Di Traglia, F., Pistolesi, M., Lestuzzi, P. (2016). Probabilistic evaluation of the physical impact of future tephra fallout events for the island of Vulcano, Italy. *Bulletin of Volcanology*. 78(5), 1-22. DOI: 10.1007/s00445-016-1028-1

Blake, D.M., Wilson, G., Stewart, C., Craig, H.M., Hayes, J.L., Jenkins, S.F., Wilson, T.M., Horwell, C.J., Andreastuti, S., Daniswara, R., Ferdiwijaya, D., Leonard, G.S., Hendrasto, M., Cronin, S. (2015). The 2014 eruption of Kelud volcano, Indonesia: impacts on infrastructure, utilities, agriculture and health, *GNS Science Report 2015/15*. 130 p.

Blake, D., Wilson, T., Deligne, N., Lindsay, J., Cole, J. (2016). Impacts of volcanic ash on road transportation: Considerations for resilience in central Auckland. *IPENZ Transportation Group Conference 7-9 March 2016.*

Blong, R. J. (1984). *Volcanic hazards. A sourcebook on the effects of eruptions*. Australia, Sydney, New South Wales: Academic Press.

Blong, R. J. (1996). Volcanic Hazards Risk Assessment, in: R. Scarpa & R.I. Tilling (Eds.), *Monitoring and mitigation of volcano hazards* (pp.676–698). Berlin, Heidelberg, Springer-Verlag.

Blong, R. (2000). Volcanic Hazards and Risk Management. In H. Sigurdsson, B.F. Houghton, S.R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes* (pp.1215-1227). San Diego: Academic Press.

Blong, R. (2003). Building damage in Rabaul, Papa New Guinea, 1994. *Bulletin of Volcanology*. 65, 43-54. DOI: 10.1007/s00445-002-0238-x

Blong, R.J., Grasso, P., Jenkins, S.F., Magill, C.R., Wilson, T.M., McMullan, K., Kandlbauer, J. (2017). Estimating building vulnerability to volcanic ash fall for insurance and other purposes. *Journal of Applied Volcanology*. 6(2). https://doi.org/10.1186/s13617-017-0054-9

Blong. R., Enright. N., Grasso. P. (2017). Preservation of thin tephra. *Journal of Applied Volcanology.* 6(10). DOI: 10.1186/s13617-017-0059-4

Bonadonna, C. (2006). Probabilistic modelling of tephra dispersion. In: H.M. Mader, S.G. Coles, C.B. Connor & L.J. Connor (Eds.), *Statistics in Volcanology: Special Publication of IAVCEI* (pp. 243–259). London: Geological Society of London.

Brown, S.K., Auker, M.R., Sparks. R.S.J. (2015) Populations around Holocene volcanoes and development of a population index. In S. Loughlin, S. Sparks, S. Brown, S. Jenkins & C. Vye-Brown (Eds.), *Global Volcanic Hazards and Risk.* (pp. 223-232). Cambridge: Cambridge University Press. DOI: http://dx.doi.org/10.1017/CBO9781316276273.006

Carey, S., Bursik, M. (2015). Volcanic plumes. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes* (2nd ed., pp.571-585). San Diego: Academic Press. DOI: http://dx.doi.org/10.1016/B978-0-12-385938-9.00032-8

Cashman, K.V., Scheu, B. (2015). Magmatic fragmentation. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes* (2nd ed., pp. 459-471). San Diego: Academic Press. DOI: http://dx.doi.org/10.1016/B978-0-12-385938-9.00025-0

Chester, D.K., Degg, M., Duncan, A.M., Guest, J.E. (2001). The increasing exposure of cities to the effects of volcanic eruptions: a global survey. *Global Environmental Change Part B: Environmental Hazards,* 2, 89–103. DOI: 10.3763/ehaz.2000.0214

Coiffier, C. (1988). Traditional Architecture in Vanuatu. Suva, Fiji: Star Printery Ltd.

Collot, J., Fisher, M.A. (1991). The collision zone between the North d'Entrecasteaux Ridge and the New Hebrides Island Arc: Sea beam morphology and shallow structure. *Journal of Geophysical Research,* 96(B3), 4457-4478.

Costa, A., Macedonio, G. and Folch, A. (2006). A three-dimensional Eulerian model for transport and deposition of volcanic ashes. *Earth Planetary Science Letters,* 241, 634–647.

Craig, H., Wilson, T., Stewart, C., Outes, V., Villarosa, G., Baxter. P. (2016a). Impacts to agriculture and critical infrastructure in Argentina after Ashfall from the 2011 eruption of the Cordón Caulle volcanic complex: An assessment of published damage and function thresholds. *Journal of Applied Volcanology*, 5(7), DOI: 10.1186/s13617-016-0046-1

Craig, H., Wilson, T.M., Stewart, C., Villarosa, G., Outes, V., Cronin, S.J., Jenkins, S. (2016b). Agricultural impact assessment and management after three widespread tephra falls in Patagonia, South America. *Natural Hazards*, 82(2), 1167-1229, DOI: http://dx.doi.org/10.1007/s11069-016-2240-1 51

Cronin, S.J., Hedley, M.J., Smith, R.G., Neall, V.E. (1997). Impact of Ruapehu ash fall on soil and pasture nutrients status 1. October 1995 eruptions. *New Zealand Journal of Agricultural Research,* 40, 383-395.

Cronin, S.J., Gaylord, D.R., Charley, D., Alloway, B.V., Wallez, S., Esau, J.W. (2004). Participatory methods of incorporating scientific with traditional knowledge for volcanic hazard management on Ambae Island, Vanuatu. *Bulletin of Volcanology*. 66, 652-668, DOI: 10.1007/s00445-004-0347-9

Deligne, N.I., Fitzgerald, R.H., Blake, D.M., Davies, A.J., Hayes, J.L., Stewart, C., Wilson, G., Wilson, T.M., Castelino, R., Kennedy, B.M., Muspratt, S., Woods, R. (2017). Investigating the consequences of urban volcanism using a scenario approach I: Development and application of a hypothetical eruption in the Auckland Volcanic Field, New Zealand. *Journal of Volcanology and Geothermal Research,* 336, 192-208. DOI: http://dx.doi.org/10.1016/j.jvolgeores.2017.02.023

Doocy. S., Daniels. A., Dooling. S., Gorokhovich. Y. (2013). The human impact of volcanoes: A historical review of events 1900-2009 and systematic literature review. *PLOS Current Disasters.* 1. DOI: 10.1371/currents.dis.841859091a706efebf8a30f4ed7a1901

Eggins, S.M. (1992). Origin and differentiation of picritic arc magmas, Ambae (Aoba), Vanuatu. *Contributions to Mineralogy and Petrology,* 114, 79-100.

Eissen, J., Blot, C., Louat, R. (1991). Chronology of the historic volcanic activity of the New Hebrides island arc from 1595 to 1991. Retrieved from: http://horizon.documentation.ird.fr/exl-doc/pleins_textes/divers13-07/34865.pdf

Freire. S., Florczyk. A.J., Pesaresi. M., Sliuzas. R. (2019). An improved global analysis of population distribution in proximity to active volcanoes, 1975-2015. *International Journal of Geo-Information,* 8, 341. DOI: 10.3390/ijgi8080341

Global Facility for Disaster Reduction and Recovery (GFDRR), (2014). Understanding risk in an evolving world: Emerging best practices in natural disaster risk assessment. International Bank for Reconstruction and Development/International Development Association for the World Bank, Washington DC. Retrieved from: https://www.gfdrr.org/sites/default/files/publication/UR-Policy_Note_0.pdf

Global Facility for Disaster Reduction and Recovery (GFDRR), (2016). Making a riskier future: How our decisions are shaping future disaster risk. Retrieved from: https://www.gfdrr.org/sites/default/files/publication/Riskier%20Future.pdf

Global Volcanism Program, (1991). Report on Ambae (Vanuatu). In: L. McClelland (ed.), *Bulletin of the Global Volcanism Network*, 16(7), Smithsonian Institution. DOI: https://doi.org/10.5479/si.GVP.BGVN199107-257030.

Global Volcanism Program, (1995). Report on Ambae (Vanuatu). In: R. Wunderman (ed.), *Bulletin of the Global Volcanism Network*, 20(8). Smithsonian Institution. DOI: https://doi.org/10.5479/si.GVP.BGVN199508-257030.

Global Volcanism Program, (2005). Report on Ambae (Vanuatu). In: R. Wunderman (ed.), *Bulletin of the Global Volcanism Network*, 30(11). Smithsonian Institution. DOI: https://doi.org/10.5479/si.GVP.BGVN200511-257030.

Global Volcanism Program, (2006). Report on Ambae (Vanuatu). In: R. Wunderman (ed.), *Bulletin of the Global Volcanism Network*, 31(1). Smithsonian Institution. DOI: https://doi.org/10.5479/si.GVP.BGVN200601-257030.

Global Volcanism Program, (2013). Report on Ambae (Vanuatu). In: R. Wunderman (ed.), *Bulletin of the Global Volcanism Network*, 38(5). Smithsonian Institution. DOI: https://doi.org/10.5479/si.GVP.BGVN201305-257030.

Global Volcanism Program, (2018a). Report on Ambae (Vanuatu). In: E. Venzke (ed.), *Bulletin of the Global Volcanism Network*, 43(2). Smithsonian Institution. Retrieved 03/07/2019 from: https://volcano.si.edu/showreport.cfm?doi=10.5479/si.GVP.BGVN201802-257030

Global Volcanism Program, (2018b). Report on Ambae (Vanuatu). In: E. Venzke (ed.), *Bulletin of the Global Volcanism Network,* 43(7). Smithsonian Institution. Retrieved 03/07/2019 from: https://volcano.si.edu/showreport.cfm?doi=10.5479/si.GVP.BGVN201807-257030

Global Volcanism Program, (2019). Report on Ambae (Vanuatu). In: E. Venzke (ed.), Bu*lletin of the Global Volcanism Network*, 44(2). Smithsonian Institution. Retrieved 03/07/2019 from: https://volcano.si.edu/showreport.cfm?doi=10.5479/si.GVP.BGVN201902-257030

Gordon, K.D., Cole, J.W., Rosenberg, M.D., Johnston, D.M. (2005). Effects of Volcanic Ash on Computers and Electronic Equipment. *Natural Hazards*, 34(2), 231–262.

Hansell, A.L., Horwell, C.J., Oppenheimer, C. (2006). The health hazards of volcanoes and geothermal areas. *Occup Environ Med*, 63, 149-156. DOI: 10.1136/oem.2005.022459

Hayes, J.L., Wilson, T.M., Magill, C. (2015). Tephra fall clean-up in urban environments. *Journal of Volcanology and Geothermal Research,* 304, 359-377. DOI: http://dx.doi.org/10.1016/j.jvolgeores.2015.09.014

Hayes, J.L., Calderón, R., Deligne, N.I., Jenkins, S.F., Leonard, G.S., McSporran, A.M., Williams, G.T., Wilson, T.M. (2019). Timber-framed building damage from tephra fall and lahar: 2015 Calbuco eruption Chile. *Journal of Volcanology and Geothermal Research*, 374, 142-159. DOI: https://doi.org/10.1016/j.jvolgeores.2019.02.017

Horwell, C.J., Baxter, P.J. (2006).The respiratory health hazards of volcanic ash: a review for volcanic risk mitigation. *Bull. Volcanol.* 69 (1), 1–24.

Horwell, C.J. (2007). Grain-size analysis of volcanic ash for the rapid assessment of respiratory health hazard. *Journal of environmental Monitoring,* 9, 1107-1115. DOI: 10.1039/b710583p

Houghton, B., Carey, R.J. (2015). Pyroclastic fall deposits. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes,* (2nd ed., pp. 599-616). San Diego: Academic Press. DOI: http://dx.doi.org/10.1016/B978-0-12-385938-9.00034-1

IVHHN. (2019). The Health Hazards of Volcanic Ash - A guide for the public. Retrieved from: https://www.ivhhn.org/ash-pamphlets

Jenkins, S., Haynes, K. (2012). Volcanic eruption. In B. Wisner, J. C. Gaillard & I. Kelman (Eds.), *Handbook of Hazards and Disaster Risk Reduction and Management.* (pp. 334-346). Oxford: Routledge.

Jenkins, S., Magill, C., McAneney, J., Blong, R. (2012). Regional ash fall hazard I: a probabilistic assessment methodology. *Bull. Volcanol,* 74(7), 1699–1712.

Jenkins, S.F., Spence, R.J.S., Fonseca, J.F.B.D., Solidum, R.U., Wilson, T.M. (2014). Volcanic risk assessment: Quantifying physical vulnerability in the built environment, 276, 105-120. http://dx.doi.org/10.1016/j.jvolgeores.2014.03.002

Jenkins, S.F., Wilson, T.M., Magill, C.R., Miller, V., Stewart, C., Marzocchi, W. and Boulton, M. (2015). Volcanic ash fall hazard and risk: Technical Background Paper for the UNISDR 2015 Global Assessment Report on Disaster Risk Reduction. Global Volcano Model and IAVCEI.

Kelman, I. (2006). Island security and disaster diplomacy in the context of climate change. *Les Cahiers de la Sécurité*, 63, 61-94.

Kelman, I., West. J.J. (2009). Climate change and small island developing states: A critical review. *Ecological and Environmental Anthropology*, 5(1).

Kelman, I., (2010). Natural disasters do not exist (Natural hazards do not exist either). Version 3, 9 July 2010. Retrieved from: http://www.ilankelman.org/miscellany/NaturalDisasters.doc

Leder, J., Wenzel, F., Daniell, J. E., Gottschämmer, E. (2017). Loss of residential buildings in the event of a re-awakening of the Laacher See Volcano (Germany). *Journal of Volcanology and Geothermal Research,* 337, 316-329. DOI: http://dx.doi.org/10.1016/j.jvolgeores.2017.02.019

Leonard, G.S., Johnston, D.M., Williams, S., Cole, J.W., Finnis, K., Bardard, S. (2005). Impacts and management of recent volcanic eruptions in Ecuador: lessons for New Zealand. *Institute of Geological & Nuclear Sciences science report*, 2005/20.

Macedonio, G., Costa, A. (2012). Brief communication “Rain effects on the load of tephra deposits”. *Natural Hazards and Earth System Science*, 12, 1229-1233. DOI: 10.5194/nhess-12-1229-2012

Mader, H.M. (1998). Conduit flow and fragmentation. In: J.S. Gilbert & R.S.J. Sparks (eds) *The Physics of Explosive Volcanic Eruptions* (pp.51-71). Geological society, London, Special publications.

MapAction. (2016). Vanuatu: Volcano – Distances from Lombenben on Ambae. Retrieved from: https://reliefweb.int/map/vanuatu/vanuatu-distances-lombenben-ambae

Maqsood, T., Wehner, M., Ryu, H., Edwards, M., Dale, K., Miller, V. (2014). GAR15 Vulnerability Functions: Reporting on the UNISDR/GA SE Asian Regional Workshop on Structural Vulnerability Models for the GAR Global Risk Assessment, 11–14 November, Geoscience Australia, Canberra, Australia. Record 2014/38. Geoscience Australia: Canberra. DOI: http://dx.doi.org/10.11636/Record.2014.038

Mercer, J., Dominey-Howes, D., Kelman, I., Lloyd, K. (2007). The potential for combining indigenous and western knowledge in reducing vulnerability to environmental hazards in small island developing states. *Environmental hazards*, 7, 245-256. DOI: doi:10.1016/j.envhaz.2006.11.001

Nairn, I.A. (2002). The effects of volcanic ash fall (tephra) on road and airport surfaces. *Institute of Geological & Nuclear Sciences science report*. 2002/13

NASA Earth Observatory. (2018, July 28). The biggest eruption of 2018 was not where you think. Retrieved from: https://earthobservatory.nasa.gov/images/144593/the-biggest-eruption-of-2018-was-not-where-you-think

NASA. (2018). Worldview. Retrieved from: https://worldview.earthdata.nasa.gov/

National Disaster Management Office [NDMO]. (2013). The Vanuatu National Disaster Management Office: Standard operating procedures. Retrieved from: http://www.ndmo.gov.vu/resources/downloads/category/16-operational-documents

National Disaster Management Office [NDMO]. (2017). Briefing pack: National Disaster Management Office, Vanuatu, November 2017. Retrieved from: http://www.ndmo.gov.vu/about-us

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018). Ambae Volcano Response: Operational summary and review 2017. Retrieved from: https://ndmo.gov.vu/images/download/VolcanoActivity-ambrym-ambae/lessons-learnt-report/ndmo-ambae-volcano-operational-summary-and-review-report-2017.pdf

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, March 20). NEOC situation update, TC Hola & Ambae volcanic activity, 20 March 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=20

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, April 11). NEOC situation update, Tropical Cyclone Hola & Ambae volcanic activity, 11 April 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=20

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, May 04). NEOC situation update, TC Hola & Ambae volcanic activity, 04 May 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=20

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, August 6). NEOC situation update, Ambae volcanic activity, 6 August 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=0

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, August 13). NEOC situation update, Ambae volcanic activity, 13 August 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=0

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, August 31). NEOC situation update, Ambae volcanic activity, 31 August 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=0

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2018, September 21). NEOC situation update, Ambae volcanic activity, 21 September 2018. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=0

National Disaster Management Office [NDMO] Government of the Republic of Vanuatu. (2019). NEOC situation update, Ambrym volcanic activity & Ambae volcanic activity, 06 February 2019. Retrieved from: https://ndmo.gov.vu/resources/downloads/category/62-situation-reports?start=20

Nemeth, K., Cronin, S.J., Harrison, M. (2006). Exploding lakes in Vanuatu – "Surtseyan-style" eruptions witnessed on Ambae Island. *EPISODES*, 29(2), 87-93.

Newhall. C.G., Self. S. (1982). The volcanic explosivity index (VEI): An estimate of explosive magnitude for historical volcanism. *Journal of Geophysical Research.* 87 (C2), 1231-1238.

Nimoho, L., Turot, O. (2017). Ambae Volcanic eruption: Food security and agricultural livelihoods (FSAL) needs assessment December 2017. Retrieved from: https://fscluster.org/vanuatu/document/ambae-volcanic-eruption-food-security

NOAA/CIMSS. (2018). Volcanic cloud imagery. Retrieved from: https://volcano.ssec.wisc.edu/imagery/view

Pacific Media Centre. (2017, September 26). Vanuatu declares state of emergency over erupting volcano *Asia Pacific Report.* Retrieved from: https://asiapacificreport.nz/2017/09/26/vanuatu-declares-state-of-emergency-over-erupting-volcano/

Pacific Media Centre. (2017, October 12). Ambae's volcano still smoking, rumbling but now 'normal' *Asia Pacific Report.* Retrieved from: https://asiapacificreport.nz/2017/10/12/ambaes-volcano-still-smoking-rumbling-but-now-normal/

Penama Province Provincial Disaster Management Plan 2002-2003. Retrieved from: https://reliefweb.int/report/vanuatu/penama-province-provincial-disaster-management-plan-2002-2003

Pomonis, A., Spence, R., Baxter, P. (1999). Risk assessment of residential buildings for an eruption of Furnas Volcano, São Miguel, the Azores. *Journal of Volcanology and Geothermal Research,* 92, 107-131.

PreventionWeb. (2015). Disaster risk reduction & disaster risk management. Accessed 21/07/19. Retrieved from https://www.preventionweb.net/risk/drr-drm

Roberts, A. (2017, September 26). VT200 Million for Ambae *Vanuatu Daily Post.* Retrieved from: http://dailypost.vu/news/vt-million-for-ambae/article_d08a1295-cb61-58ce-97ef-3a030101ccf8.html

Robin, C., Monzier, M., Crawford, A. J., Eggins, S. M., (1993). The geology, volcanology, petrology-geochemistry, and tectonic evolution of the New Hebrides island arc, Vanuatu. *IAVCEI Canberra 1993 excursion guide*, Aust Geol Surv Org, 86 p.

Roof, K., Oleru, N. (2008). Public health: Seattle and King County's push for the built environment. *Journal of Environmental Health,* 71(1), 24-27

Rouland, D., Cisternas, A., Denkmann, R., Dufumier, H., Regnier, M., Lardy, M. (2001). The December 1994 seismic swarm near Aoba (AMBAE) volcano, Vanuatu, and its relationship with the volcanic processes. *Tectonophysics,* 338(1), 23–44.

Scasso, R.A., Corbella, H., Tiberi, P. (1994). Sedimentologocal analysis of the tephra from the 12-15 August 1991 eruption of Hudson volcano. *Bulletin of Volcanology*, 56, 121-132

Segerstrom, K. (1950). Erosion studies at Paricutin, State of Michocan, Mexico: U.S. *Geological Survey Bulletin*. 965, 1-164.

Shultz, J.M., Cohen, M.Z., Hermosilla, S., Espinel, Z., McLean, A. (2016). Disaster risk reduction and sustainable development for small island developing states. *Disaster Health*, 3(1). 32-44. DOI: 10.1080/21665044.2016.1173443

Sparks, R.S.J., Bursik, M.I., Carey, S.N., Gilbert, J.S., Glaze, L.S., Sigurdsson, H., Woods, A.W. (1997). *Volcanic Plumes*. John Wiley & Sons Ltd. West Sussex, England.

Sparks, R.S.J., Aspinall, W.P., Crosweller, H.S., Hincks, T.K. (2013). Risk and uncertainty assessment of volcanic hazards. In: J. Rougier, S. Sparks & L. Hill (eds). *Risk and uncertainty assessment for natural hazards* (pp. 364 – 397). Cambridge University Press.

Spence, R.J.S., Pomonis, A., Baxter, P.J., Coburn, A.W., White, M., Dayrit, M., Field Epidemiology Program Team. (1996). Building damage caused by the Mount Pinatubo eruption of June 15, 1991. In: C.G. Newhall & R.S. Punongbayan (eds) *Fire and mud: eruptions and lahars of Mount Pinatubo, Philippines* (pp. 1055–1061). Philippine Institute of Volcanology and Seismology, University of Washington Press, Seattle.

Spence, R. J. S., Kelman, I., Baxter, P. J., Zuccaro, G., Petrazzuoli, S. (2005). Residential building and occupant vulnerability to tephra fall. *Natural Hazards and Earth System Sciences*, 5, 477-494

Standards Australia/Standards New Zealand. (2009). Risk Management - principles and guidelines (AS/NZS ISO 31000:2009).

Stewart, C., Johnston, D.M., Leonard, G.S., Horwell, C.J., Thordarson, T., Cronin, S.J. (2006). Contamination of water supplies by volcanic ashfall: A literature review and simple impact modelling. *Journal of Volcanology and Geothermal Research*, 158, 296-306. DOI: 10.1016/j.jvolgeores.2006.07.002

Tarasenko. I., Bielders. C.L., Guevara. A., Delmelle. P. (2019). Surface crusting of volcanic ash deposits under simulated rainfall. *Bull Volcanol,* 81 (30). DOI: https://doi.org/10.1007/s00445-019-1289-6

Tariseisei, J. (1998). Today is not the same as yesterday, and tomorrow it will be different again: Kastom on Ambae, Vanuatu. Retrieved from: http://dlib.vanuatu.usp.ac.fj/library/Online/Vanuatu/Tarisesei.htm

UNDRR. (2017) Terminology on Disaster Risk Reduction. Retrieved from: https://www.unisdr.org/we/inform/terminology#letter-d

UNDRR. (2019) What is Disaster Risk Reduction? Retrieved from: https://www.unisdr.org/who-we-are/what-is-drr

United Nations. (2014). 69/15. SIDS Accelerated Modalities of Action (SAMOA) Pathway. Retrieved from: https://www.un.org/ga/search/view_doc.asp?symbol=A/RES/69/15&Lang=E

United Nations. (2015). Sendai Framework for Disaster Risk Reduction 2015-2030. Retrieved from: https://www.unisdr.org/we/inform/publications/43291

United Nations International Strategy for Disaster Reduction. (2009, May) 2009 UNISDR Terminology on Disaster Risk Reduction. Retrieved from: https://www.unisdr.org/we/inform/publications/7817

United Nations International Strategy for Disaster Reduction (UNISDR). (2015). Reading the Sendai Framework for Disaster Risk Reduction 2015-2030. Retrieved from: https://www.preventionweb.net/publications/view/46694

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2014). Vanuatu Volcano Alert Level System. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/volcano-info/volcanic-alert-level

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2017a). Vanuatu Volcano Alert Bulletin N°9 – Ambae Activity. Wednesday September 6th 2017. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2017b). Vanuatu Volcano Alert Bulletin N°11 – Ambae Activity. Saturday September 23rd 2017. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2017c). Vanuatu Volcano Alert Bulletin N°16 – Ambae Activity. Thursday December 7th 2017. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2018a). Vanuatu Volcano Alert Bulletin N°5 – Ambae Activity. Thursday June 7th 2018. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2018b). Vanuatu Volcano Alert Bulletin N°7 – Ambae Activity. Saturday July 21st 2018. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (2018b). Vanuatu Volcano Alert Bulletin N°9 – Ambae Activity. Friday September 21st 2018. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/alert-bulletin/

Vanuatu Metorology & Geo-hazards Department [VMGD]. (n.d.). Manaro Voui Volcano: Most recent eruptions. Retrieved from: https://www.vmgd.gov.vu/vmgd/index.php/geohazards/volcano/our-active-volcanos/ambae/manaro-voui

Vanuatu National Statistics Office [VNSO]. (2016). 2016 Post tropical cyclone Pam mini census report, Vol 1. Retrieved 10/12/2018 from: https://vnso.gov.vu/index.php/component/advlisting/?view=download&fileId=4542

Vanuatu National Disaster management Office [NDMO]. (2018). Meawo response & recovery action plan, Ambae volcano. Retrieved from: https://ndmo.gov.vu/ambae-volcano-activity/category/67-reports

Volcanic Ash Working Group. (2015). Volcanic ash. Retrieved from: https://volcanoes.usgs.gov/volcanic_ash/ash.html

Warden, A. J. (1970). Evolution of Aoba Caldera volcano, New Hebrides. *Bull Volcanol*, 34, 107-140.

Wardman, J., Wilson, T.M., Bodger, P.S., Cole, J.W., Stewart, C., (2012b). Potential impacts from tephra fall to electric power systems: a review and mitigation strategies. *Bull. Volcanol*, 74, 2221–2241.

Wilson, G., Wilson, T.M., Deligne, N.I., Cole, J.W. (2014). Volcanic hazard impacts to critical infrastructure: A review. *Journal of Volcanology and Geothermal Research*, 286, 148-182. DOI: http://dx.doi.org/10.1016/j.jvolgeores.2014.08.030

Wilson, T.M., Cole, J.W. (2007). Potential of a tephra eruption on a dairy farm in eastern Bay of Plenty, New Zealand; implications for hazard mitigation. *Natural Hazards*, 43, 103-128.

Wilson, T., Kaye, G., Stewart, C., Cole, J. (2007). Impacts of the 2006 eruption of Merapi volcano, Indonesia, on agriculture and infrastructure. *GNS Science Report,* 2007/07.

Wilson, T.M., Kaye, G.D. (2007b). Agricultural fragility estimates for volcanic ash fall hazards. *GNS Science Report,* 2007/37

Wilson, T., Stewart, C., Cole, J., Johnston, D., Cronin, S. (2010). Vulnerability of farm water supply systems to volcanic ash fall. *Environmental Earth Sciences,* 61, 675-688. DOI: 10.1007/s12665-009-0380-2

Wilson, T.M., Cole, J.W., Stewart, C., Cronin, S.J., Johnston, D.M. (2011a). Ash storms: impacts of wind-remobilised volcanic ash on rural communities and agriculture following the 1991 Hudson eruption, southern Patagonia, Chile. *Bull Volcanol*, 73, 223-239. DOI: 10.1007/s00445-010-0396-1

Wilson, T., Cole, J., Cronin, S., Stewart, C., Johnston, D., (2011b). Impacts on agriculture following the 1991 eruption of Vulcan Hudson, Patagonia: Lessons for recovery. *Natural Hazards*. 57, 185-212. DOI: 10.1007/s11069-010-9604-8

Wilson, T., Stewart, C., Sword-Daniels, V., Leonard, G.S., Johnston, D.M., Cole, J.W., Wardman, J., Wilson, G., Barnard, S.T. (2012). Volcanic ash impacts on critical infrastructure. *Physics and Chemistry of the Earth*, 45-46, 5-23. DOI: 10.1016/j.pce.2011.06.006

Witham, C.S., Oppenheimer, C., Horwell, C.J. (2005). Volcanic ash-leachates: A review and recommendations for sampling methods. *Journal of Volcanology and Geothermal Research*, 141(3-4), 299–326.

World Bank Group. (n.d.). Vanuatu. Retrieved: 25/07/2019 from: https://climateknowledgeportal.worldbank.org/country/vanuatu/climate-data-historical

Wright. K.C., Johnston. D.M. (2010) Post-earthquake sheltering needs; how loss of structures and services affects decision making for evacuation. *2010 NZSEE Conference.* Paper 31. Retrieved from: https://www.nzsee.org.nz/db/2010/Paper31.pdf

Zimanowski, B., Büttner, R., Dellino, P., White, J.D.L., Wohletz, K.H. (2015). Magma-water interaction and phreatomagmatic fragmentation. In H. Sigurdsson, B. F. Houghton, S. R. McNutt, H. Rymer, & J. Stix (Eds.), *Encyclopedia of Volcanoes* (2nd ed., pp. 473-484). San Diego: Academic Press. DOI: http://dx.doi.org/10.1016/B978-0-12-385938-9.00026-2

APPENDICES

Appendix A. BACKGROUND MATERIAL ON DISASTER RISK REDUCTION

A.1 Sendai Framework for Disaster Risk Reduction 2015-2030

The Sendai Framework for Disaster Risk Reduction 2015-2030 is a voluntary, non-binding agreement for UN Member States, whose role is to reduce disaster risk with the collaboration of stakeholders. The Sendai Framework is the successor to the Hyogo Framework for Action (HFA) 2005-2015: Building the Resilience of Nations and Communities to Disasters. The Sendai Framework has been developed from elements of the HFA to ensure continuity across the work already achieved by UN Member States in reducing disaster risk (United Nations, 2015), while still positively developing society's attitude towards disaster risk reduction. The outcome which the Sendai Framework aims to achieve from 2015-2030 is the substantial reduction of risk of, and losses from disasters in all aspects of society (United Nations, 2015).

The Sendai Framework's realigned-focus now puts stronger emphasis on disaster risk management, rather than the Hyogo Framework's disaster management, outlined by four priorities and seven global targets (United Nations, 2015). Priority one is understanding disaster risk, which this thesis contributes toward by developing the current understanding of how tephra fall can impact traditional buildings in the Pacific. Priority one involves understanding the dimensions of disaster risk including the vulnerability and capacity of exposed assets, hazard characteristics and the local environment (United Nations, 2015). The underlying purpose of understanding disaster risk is so that pre-disaster risk assessments can be carried out and inform actions that will contribute towards the Sendai Framework's outcome of reducing disaster risk.

A.2 UNISDR definitions

Hazard: refers to "*a process, phenomenon or human activity that may cause loss of life, injury or other health impacts, property damage, social and economic disruption or environmental degradation"* (UNDRR, 2017). Under the concept of 'risk' hazard refers to the likelihood and intensity of the dangerous phenomena (GFDRR, 2014).

Exposure: refers to "*the situation of people, infrastructure, housing, production capacities and other tangible human assets located in hazard-prone areas*" (UNDRR, 2017). As DRR has developed, exposure has shifted from a focus on people to also include other societal elements such as buildings, infrastructure and agriculture as they too are crucial in maintaining a functional society.

Vulnerability: is "*the conditions determined by the physical, social, economic and environmental factors or processes which increase the susceptibility of an individual, a community, assets or systems to the impacts of hazards*" (UNDRR, 2017).

Impacts: are the effects (both negative and positive) as a result of a disaster and may include economic, environmental, human and social impacts (UNDRR, 2017). In this thesis, the term impact is used to describe both the physical damage and disruption tephra fall can cause to buildings.

Appendix B. VANUATU NATIONAL STATISTICS OFFICE (VNSO) POST-CYCLONE PAM CENSUS DATA

The following section provides data on Ambae's population from a post-Cyclone Pam (2015) census collected by VNSO used to establish the risk context by describing Ambae's population demographics and lifestyle in section 2.2.1

Table B.1 Number of households by land tenure type. Data source VNSO (2016)

Region	Land Tenure type				
	Customary	**Rural lease**	**Urban lease**	**Occupy with informal arrangements**	**Other**
West Ambae	795	14	-	18	-
North Ambae	751	14	-	34	-
East Ambae	420	99	-	7	-
South Ambae	330	-	-	-	-

Table B.2 Number of households growing key crops. Data source VNSO (2016)

Region	Vegetables type							
	Kumala	**Island cabbage**	**Yam**	**Pawpaw**	**Island/water taro**	**Fijian taro**	**Manioc/cassava**	**Banana**
West Ambae	604	798	653	679	473	638	788	786
North Ambae	662	778	591	665	715	573	749	739
East Ambae	359	455	260	161	346	161	440	446
South Ambae	318	329	266	285	265	236	323	309

Table B.3 Ambae households' primary source of income. Data Source VNSO (2016)

Region	Main Source of household income							
	Public sector	**Land lease**	**Remittances**	**House rent**	**Sale of fish/crops /handicrafts**	**Own business**	**Others**	**None**
West Ambae	143	-	95	1	714	194	145	1
North Ambae	142	3	52	-	664	113	24	8
East Ambae	197	1	6	3	354	126	13	13
South Ambae	13	-	4	-	297	65	21	2
Total	14%	<1%	5%	<1%	59%	15%	6%	1%

Table B.4 Number of Ambae Households growing cash crops. Data source VNSO (2016)

Region	Cash Crop types			
	Cocoa	Coconut	Coffee	Kava
West Ambae	588	606	7	376
North Ambae	63	309	-	570
East Ambae	2	10	-	248
South Ambae	42	88	4	168

Table B.5 Number of Ambae households that own livestock. Data source VNSO (2016)

Region	Household livestock ownership				
	Cattle	Pig	Poultry	Goat	No livestock
West Ambae	276	496	803	42	18
North Ambae	152	491	712	7	23
East Ambae	138	265	427	2	62
South Ambae	167	115	134	27	45

Table B.6 Ambae households' primary drinking water source. Data source VNSO (2016)

	Main source of drinking water							
Region	Piped - private	Piped - shared	Village stand pipe	Rainwater well / tank private	Rainwater Well/tank - shared	Bottled water	River, stream, creek, lake, spring	Underground borehole/well
West Ambae	-	-	-	561	252	3	2	9
North Ambae	49	31	7	347	312	-	28	23
East Ambae	8	7	1	198	285	2	-	22
South Ambae	19	28	6	134	103	-	40	-

Appendix C. Tephra fall hazard

The following section provides further detail on how volcanic tephra is formed, its physical and chemical properties and how tephra fall is dispersed.

C.1 Formation of volcanic tephra

Tephra produced during explosive volcanic eruptions is formed through two different mechanisms of magma fragmentation (Cashman & Scheu, 2015). Magmatic fragmentation is driven by gases (primarily H_2O, CO_2 and S (Mader, 1998)) dissolved in the magma that nucleates as the magma decompresses through conduit ascent or lava dome collapse (Cashman & Scheu, 2015). As the gas nucleates and expands fragmentation turns the liquid magma and gas phases into gas and magma fragments (tephra) (Cashman & Scheu, 2015). Phreatomagmatic fragmentation results from a complex interaction between magma, gases, wall rock and water (Zimanowski et al. 2015). Fragmentation occurs when the hot magma is cooled, contracts and fractures when it comes into contact with cooler water (Sparks et al. 1997).

C.2 Properties of tephra

The physical properties of tephra is mostly determined by the eruption style with the chemical properties of tephra depending on magma composition and volatile composition. Understanding the physical and chemical properties of tephra produced during an eruption is important as these properties will influence the impact tephra fall may have on people, infrastructure, agriculture and buildings.

C.2.1 Particle size

The particle sizes of tephra is defined as blocks and bombs (>64 mm), lapilli (2-64 mm) and ash (<2 mm). Particle size depends upon the size of an eruption, the amount of energy during fragmentation and magma composition. The size of a tephra particle can influence the mechanism in which it travels and the distance it can reach from the vent. Large block and bomb particles will likely travel in ballistic trajectories and remain proximal to the active vent (Blong, 1984). Ash particles will typically become entrained in an eruptive plume and potentially travel many kilometres from the eruption vent (Sparks et al. 1997).

C.2.2 Density

Density of tephra is it mass per unit volume. The density of an individual tephra particle depends upon its size (volume) and composition (mass). Pumice, which is highly vesicular and is full of voids can have a density as low as 700 kg/m^3 whereas crystals can have a density up to 3300 kg/m^3 (Volcanic Ash Working Group, 2015). The density of a tephra fall deposit will depend upon the shape of the tephra particles and moisture content of the deposit (Volcanic Ash Working Group, 2015). The density of dry tephra fall deposits can range from 500 to 1,500 kg/m^3 whereas a wet deposit can range from 1,000 to 2,000 kg/m^3 (Volcanic Ash Working Group, 2015).

C.2.3 Composition

Tephra can be composed of volcanic glass (vitrics), minerals and crystals, or rock fragments (lithics) (Sparks et al. 1997). The chemistry of volcanic glass, mineral and crystal tephra components depend on the chemistry of the source magma. Volcanic glass is formed when magma cools fast enough that crystallisation cannot occur and are usually very angular particles (Sparks et al. 1997). Minerals and crystals form when the magma cools over a prolonged length of time allowing for crystallisation to occur which occurs while the magma was still below the Earth's surface (Volcanic Ash Working Group, 2015). Rock fragments are fragments of other rocks, sourced from the rocks that surround the magma chamber or conduit. As magma ascends its movement can mechanically remove fragments of surrounding rock, incorporating them into the magma and erupted material (Sparks et al. 1997).

C.2.4 Abrasiveness

The abrasiveness of tephra is determined by the shape, composition and hardness of the tephra particle (Wilson et al. 2012). Tephra particles that are angular and sharp (e.g. volcanic glass) or are hard (e.g. quartz crystals) are more abrasive. Tephra can abrade a surface in three different ways; two-body abrasion, three body abrasion and erosion (Gordon et al. 2005). Two-body abrasion occurs when tephra becomes imbedded in surface and abrades against another surface (e.g. tephra imbedded in a cloth used to clean a surface) (Gordon et al. 2005). Three-body abrasion is where tephra is free to abrade between two surfaces (Gordon et al. 2005) (e.g. tephra in the lubricant of machines and motors). Erosion is where tephra impacts a surface, removing part of that surface (Gordon et al. 2005) (e.g. tephra impacting the windshield of a moving vehicle).

C.2.5 Soluble surface coating

Common gases released during volcanic eruptions include water, carbon dioxide, carbon monoxide, sulphur dioxide, hydrogen sulphide, hydrogen fluoride and hydrogen chloride (Witham et al. 2005). One of the mechanisms by which erupted gases are removed from the atmosphere is by absorbing onto the surface of tephra particles forming a soluble salt coating (Witham et al. 2005). Once tephra with a soluble salt coating is deposited, water is able to dissolve the soluble salt coating mobilising the salt ions into the ground or water. The controls that determine if elements are absorbed onto the surface of tephra include; magma and tephra composition, eruption style, dispersion of tephra and gas, tephra to gas ratio, tephra size and surface area, temperature and environmental conditions (Witham et al. 2005). Tephra with a surface coating can also become conductive when wet allowing a pathway for electrons to flow freely (Wilson et al. 2012).

C.3 Dispersal of tephra fall

Convective eruption columns (tephra plumes) form when magma that has fragmented into solid particles, gasses and some liquids are ejected from a vent at high velocity into the atmosphere (Sparks et al. 1997). A convective eruption column comprises of three regions based upon the dominant forces controlling the plumes motion (Sparks et al. 1997); the gas thrust region, convective region and umbrella region (Figure B.1). In the gas thrust region the bulk density of the eruption column is greater than the surrounding atmosphere and it is the momentum of the column that causes it to rise rather than buoyancy. If the column is able to entrain and heat enough atmospheric air the gas thrust region will reduce its buoyancy to less than the surrounding atmosphere and begin to rise buoyantly (Sparks et al. 1997). If an eruption column is unable to reduce its buoyancy it will collapse and form a pyroclastic density current or surge (Sparks et al. 1997).

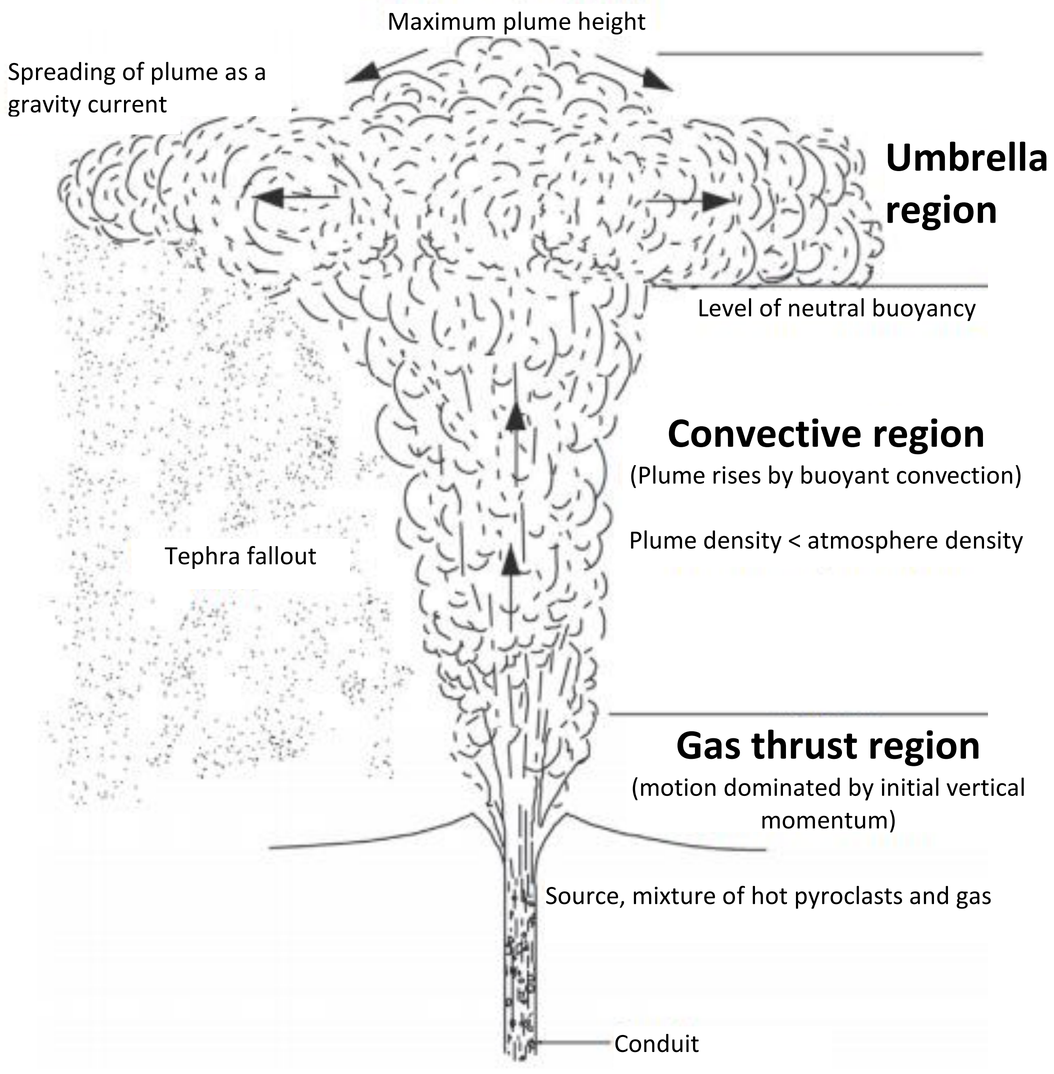

Figure C. 1 Conceptual model of the processes within an eruption plume (modified from Carey & Bursik, 2015)

In the convective region the eruption column has a lower density than the surrounding air and the forces which drive the upward movement are dominated by buoyancy and the expansion of air (Sparks et al. 1997; Carey & Bursik, 2015). The convective region can extend for tens of kilometres into the air (Carey & Bursik, 2015) and the column will often widen as more air becomes entrained (Sparks et al. 1997). The density of the Earth's atmosphere decreases with height and eventually the convective region will reach a height where the density of the column is equal to that of the surrounding atmosphere (Sparks et al. 1997; Carey & Bursik, 2015). This is the level of neutral buoyancy were the eruption column is no longer driven by buoyancy and will begin to travel laterally, forming the umbrella region (Carey & Bursik, 2015). Because buoyancy is no longer acting upon the eruption column in the umbrella region it will be carried laterally down-wind by the present atmospheric currents.

Eventually gravity will overcome tephra particles in the umbrella region and tephra will begin to fallout of the eruption column, producing a tephra fall deposit. The largest and heaviest tephra particles entrained in the umbrella region will fallout first while smaller and lighter tephra particles continue to be carried down-wind (Blong 1984). As tephra particles fallout the density and particle concentration in the umbrella region decrease. The speed that the umbrella region travels will eventually match the wind speed and its motion will become dominated by the wind allowing tephra to travel over 100s of kilometres (Carey & Bursik, 2015). As a result the tephra fall deposit will reflect what is happening in the umbrella region and the thickness, particle size and concentration will decrease with distance from the active vent (Houghton & Carey, 2015).

Tephra dispersal and deposition is influenced by the total volume of erupted material and eruption column height (Volcanic Explosivity Index), the mass eruption rate, grain size distribution of the tephra and atmospheric conditions during emplacement and transportation (Carey & Bursik, 2015). The Volcanic Explosivity Index (VEI), is a nine scale index ranging from 0 (non-explosive Hawaiian eruption) to 8 (Ultra-Plinian eruption) which describes the volume of erupted material and eruption column height (Newhall & Self, 1982). The more material that is injected into the atmosphere, and the higher the eruption plume reaches in the atmosphere, the more widely tephra fall is going to be dispersed (Carey & Bursik, 2015). The direction the tephra plume travels, and tephra fall is dispersed will depend upon the wind direction at the time of the eruption (Carey & Bursik, 2015). As a result, tephra can travel great distances in excess of 100 km, and affect large geographical areas (Wilson & Cole, 2007).

Appendix D. TEPHRA FALL IMPACT

D.1 Human health

The direct impacts of tephra fall and tephra particles on human health are not usually immediately life-threatening, with the exceptions of roof collapse from tephra loading and fatal falls from roofs or ladders during clean-up operations (Spence et al. 2005; Hayes et al. 2015). However, airborne tephra may still threaten public health by causing irritation and respiratory issues (Horwell & Baxter, 2006). Particle size, acidic coating and abrasive properties of tephra can cause skin and eye irritation (Hansell et al. 2006; IVHHN, 2019) (Figure D.1). The severity of respiratory ailments from the inhalation of tephra depends primarily on the grainsize of the tephra particles. Particles smaller than 10 µm can enter the lungs and cause bronchitis, asthma and silicosis (Horwell, 2007; Baxter & Horwell, 2015). Drinking water contaminated by tephra can have high levels of turbidity which may interfere with disinfection and thus lead to an increase in outbreaks of waterborne diseases (Stewart et al. 2006).

Figure D.1 Field team on Ambae wearing dust masks to prevent inhaling fine tephra particles billowed by the moving vehicle

Indirect impacts from tephra fall can include drinking water contamination and crop damage. Tephra can contaminate drinking water with elements such as fluoride, which in high concentrations can cause dental and skeletal fluorosis, or metallic elements such as iron, aluminium, manganese and copper which can impart an unpleasant taste to the water at low concentrations and be toxic at higher concentrations (Stewart et al., 2006).

D.2 Infrastructure

Society is served by a wide range of infrastructure facilities and systems that include, but are not limited to; electricity networks, roads, water supplies, wastewater systems and telecommunications. In the last decade, many studies have assessed the impact volcanic hazards can have on infrastructure, but there is still a lack of robust vulnerability models (Wilson et al. 2014). Furthermore these studies focused on developed infrastructure networks that are not necessarily applicable for the infrastructure present on Ambae. Damage and disruption to infrastructure is likely to have the greatest impact on society (Jenkins et al. 2014) due to the interdependencies between and within infrastructure networks and society (Wilson et al. 2012). The mechanism by which tephra fall impacts infrastructure depends not only on the properties of the tephra, but also the type of infrastructure component exposed (Wilson et al. 2014). A summary of some of the key impacts tephra fall has on infrastructure systems are provided in Table D.1.

Table D.1 Summary of the key impacts of tephra fall on selected infrastructure systems

Infrastructure system	Tephra fall impact	Reference
Electricity systems	• Insulator flashover • Physical abrasion • Corrosion of metal surfaces • Physical damage to lines	• Jenkins et al. 2014 • Wilson et al. 2009, 2012, 2014 • Wardman et al. 2012
Water supply systems	• Water contamination • Clogging of open air sand filters • Damage to intake structures • Abrasive damage to pump impellers • Loss of electricity	• Stewart et al. 2006 • Wilson and Cole, 2007 • Wilson et al. 2010, 2012, 2014 • Jenkins et al. 2014 • Craig et al. 2016a
Road network systems	• Reduced road traction • Covered road markings • Reduced visibility	• Nairn, 2002 • Leonard et al. 2005 • Wilson et al. 2012 • Jenkins et al. 2014 • Blake et al. 2016
Wastewater systems	• Blocked catchpits and sewer lines • Power outages affecting pumping stations • Damage to mechanical pre-treatment equipment • Reduced capacity of open air bioreactors	• Wilson et al. 2012 • Jenkins et al. 2014
Telecommunication systems	• Signal interference • Corrosion of metal surfaces • Network overloading	• Wilson et al. 2009, 2012, 2014

D.3 Agriculture

Understanding of the impact tephra fall has on agriculture is the least developed when compared to the impacts to human health, infrastructure and buildings. All agricultural sectors are vulnerable to the chemical and physical properties of tephra fall, which can impact soils, vegetation, livestock, infrastructure and machinery (Wilson et al. 2011b). Thick tephra falls (> 100 mm in depth) can have a severe impact on agriculture, but even thin tephra fall deposits can have substantial impact on some agricultural system components (Wilson et al. 2011b). The complexity of agricultural systems means that the impact of tephra fall depends not only on the thickness of tephra but also the magnitude, duration and frequency of tephra falls and the particle size, soluble coating and mineralogy of the tephra (Wilson et al. 2011b). The impacts tephra fall can have on agriculture, identified by Wilson & Kaye (2007) include;

- Limiting photosynthesis capability of crops and pasture (Figure D.2a).
- Physical breakage, mechanical abrasion and burial of crops and pasture (Figure D.2c).
- Irritation of the eyes and skin of livestock, ingestion of tephra, respiratory issues and abrasion of teeth and hooves.
- Contamination to pasture and water for livestock leading to dehydration and/or starvation (Figure D.2b).
- Soil chemistry changes.

Figure D. 2 Agricultural impacts observed on Ambae. (a) Island cabbage damaged by tephra fall (b) malnourished cattle (c) damaged coconut trees

Appendix E. Detailed chronology for the 2017/18 eruption period of Manaro Voui volcano

E.1 Phase 1: September - November 2017

E.1.1 Volcanic processes in Phase 1

The first phase, involved the formation, destruction and reconstruction of a pyroclastic cone that surrounded the active vent, lava flows and small tephra and gas emissions (Figure E.1) (VMGD n.d.) Most volcanic processes were contained within the boundary of the summit calderas. The exceptions were small tephra plumes that produced thin tephra deposits across Ambae and volcanic gasses released into the atmosphere that interacted with atmospheric water, producing acid rain. While most of the volcanic processes were contained within the summit caldera, neighbouring islands of Espiritu Santo, Maewo and Pentecost regularly reported being able to see tephra plumes and 'glows' from the summit region (Global Volcanism Programme 2018a). Residents of Ambae and the other neighbouring islands also reported hearing large 'bangs' or 'explosions' associated with these volcanic processes (Pacific Media Centre 2017, October 12) contributing to the fear that eruptive activity may increase and cause greater damage and disruption to the Ambae.

E.1.2 Volcanic hazard impacts of Phase 1

Impacts from the first eruption phase were to vegetation and water sources from tephra fall and acid rain; there were no reports of any building damage. Vegetation near the eruptive vent was stripped of all of its foliage, leaving only bare tree trunks (Figure E.1a). Further from the vent crops grown by families were damaged by tephra fall and acid rain to where some crops became unfit for consumption. Rainwater fed tanks used for drinking water were contaminated by tephra fall and acid rain when appropriate mitigation methods were not put in place to prevent tephra or acid rain from entering. While the primary cause of crop damage was attributed to tephra fall and acid rain, there were also indirect sources of crop damage reported by residents. The most common indirect crop damage reported was caused by livestock that had been released while people were evacuated off the island (Nimoho & Turot 2017). Other indirect causes of crop damage included the dry season, theft, pests and the lack of care while people were evacuated (Nimoho & Turot 2017).

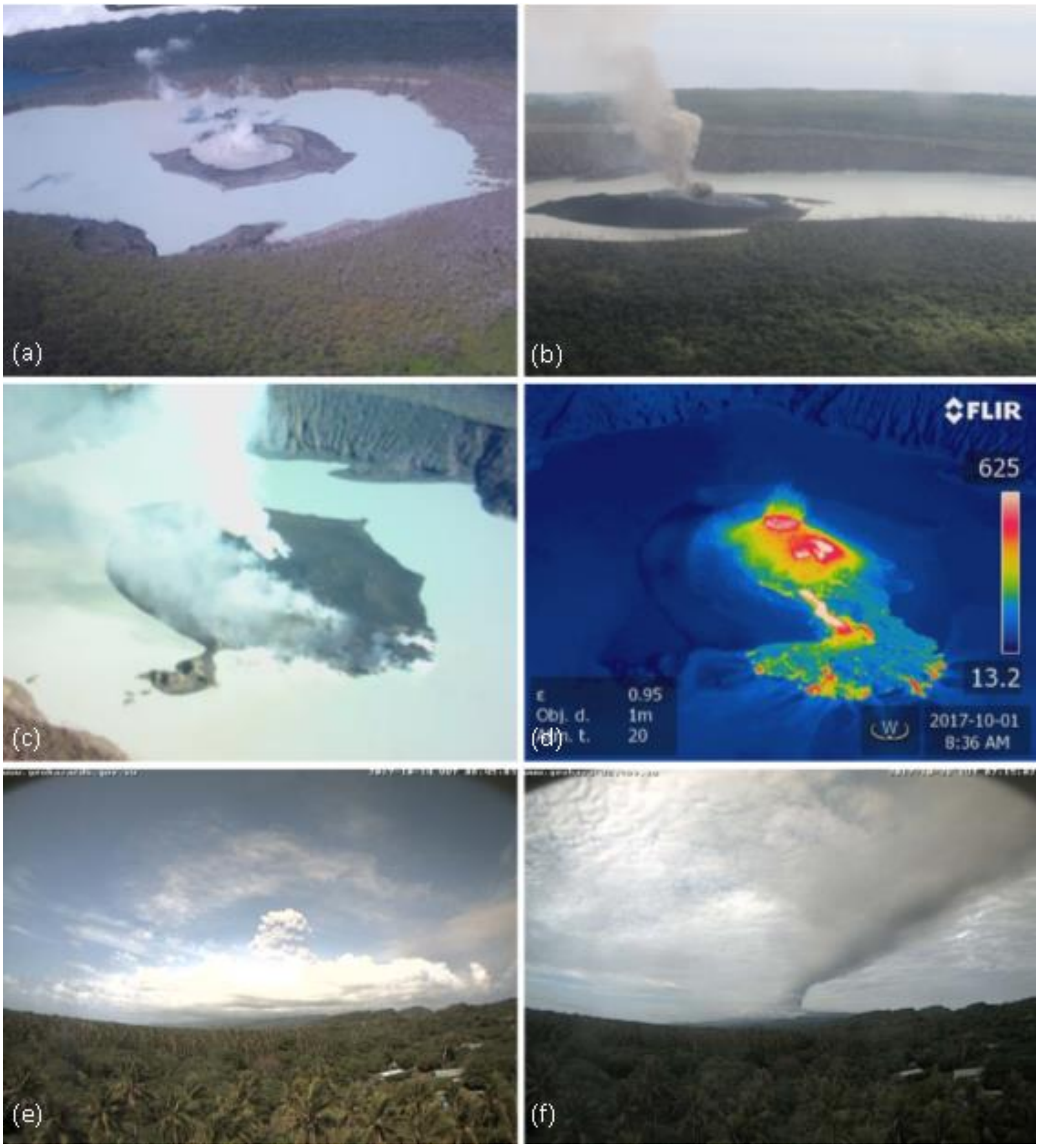

Figure E.1 Series of photos showing the range of activity from Manaro Voui during phase 1 of its eruption period. (a) Pyroclastic cone in the centre of Lake Vui on 09/09/2017 (photo source: VMGD) (b) Pyroclastic cone that was growing from Manaro Voui's eruptive activity on 24/09/2017 (photo source: VMGD) (c) The pyroclastic cone and a lava flow that was flowing into Lake Vui 01/10/2017 (Photo source: Brad Scott GNS) (d) Infra-red image of the pyroclastic cone highlighting the lava flow 01/10/2017 (Photo source: Brad Scott GNS) (e) VMGD webcam view of an tephra plume from the eruption on the 14/10/2017 (photo source: VMGD) (f) VMGD webcam view of a tephra plume being carried down-wind from an eruption on 26/10/2017 (photo source: VMGD).

E.1.3 Emergency response to Phase 1

On the 6th September 2017 VMGD upgraded the VAL of Manaro Voui from 2 to 3 indicating Manaro Voui was in a minor state of eruption (VMGD 2017a). During the 1st -28th September 2017, Penama's EOC began coordinating an emergency response for the ongoing volcanic activity. Villages to the south and west of the active vent were evacuated to evacuation centres set up at the extremities of the island in Lolowai and Walaha (NDMO 2018). During this time VMGD continued to closely monitor Manaro Voui and distribute volcanic hazard information, working closely with international volcanologists from GNS Science New Zealand and the Institut de Recherche pour le Développement (IRD, France) and Vanuatu's NDMO began distributing information raising awareness on health and safety (NDMO 2018).

The VAL of Manaro Voui was further upgraded to a VAL of 4 on the 23rd September, indicating the volcano was in a moderate eruptive state and that villages on Ambae may experience tephra falls and acid rain (VMGD 2017b). In response to the eruptive activity from Manaro Voui on the 26th September 2017 Vanuatu's Government declared a state of emergency allowing public funds to become available to assist the emergency response (Pacific Media Centre 2017, September 26). The Government released 200 million vatu (NZD $2.6 million) for the emergency to assist with evacuations and providing evacuees with shelter, food and water (Roberts 2017, September 26). The issuing of the state of emergency, combined with the ongoing activity at Manaro Voui resulted in the Council of Ministers deciding to issue a compulsory evacuation of Ambae's approximate population of 11,000 (Australian Humanitarian Partnership 2017). The whole-island evacuation began on the 29th September and was completed on the 6th October. Most residents of Ambae were evacuated to the nearby islands of Espiritu Santo, Maewo and Pentecost and those who evacuated to other islands did so at their own expense (NDMO 2018).

On the 6th October 2017 VMGD lowered Manaro Voui's VAL to 3 and the Council of Ministers made the decision for repatriation and re-establishment of communities back to Ambae (NDMO 2018). On the 10th October the Council of Ministers extended the state of emergency by two weeks to ensure there were enough resources to facilitate the repatriation (NDMO 2018). Between the 22nd October and 1st November 2017 most of Ambae's pre-eruption population returned to Ambae with secondary school students remaining on their host islands until the end of the school year (NDMO 2018).

E.2 Phase 2: December 2017 - February 2018

E.2.1 Volcanic processes in Phase 2

Phase 2 represented a period of heightened degassing and steam emissions (VMGD 2017c) with a few minor eruptions producing tephra fall. Manaro Voui released sulphur dioxide (SO_2) into the atmosphere that reacted with water and oxygen to produce sulphuric acid which when mixed with rainwater, lowered the water's pH creating acid rain. Most of the acid rain that occurred during phase 2 was reported to the west and southwest of the active vent.

E.2.2 Volcanic hazard impact of Phase 2

Residents of Ambae reported that acid rain was damaging crops, by 'burning' leaves. Vegetable crops like island cabbage were more vulnerable to acid rain than root crops including taro, manioc and kumala (Nimoho & Turot 2017). Some water sources continued to be contaminated and had a 'sour' taste from the acid. Acid rain would have of also accelerated corrosion of metal surfaces such as sheet metal roof or water tap fittings, however these impacts were not immediately evident.

E.2.3 Emergency response to Phase 2

On the 7th December 2017 VMGD lowered Manaro Voui's VAL from 3 to 2 indicating that Manaro Voui was now in a state of major volcanic unrest (VMGD 2017c). Manaro Voui remained at this VAL throughout all of phase 2. During phase 2 VMGD continued to monitor Manaro Voui and provide information to the public on Ambae's state and volcanic hazards.

E.3 Phase 3: February - April 2018

E.3.1 Volcanic processes in Phase 3

During phase 3 Manaro Voui began to erupt again, producing multiple tephra falls as well as continuing to produce acid rain towards the south and west of the active vent. There were three eruptions in particular that produced thick tephra fall deposits resulting in damage to some exposed buildings (Figure E.3, Table 3.3). The first substantial tephra fall on the 15-16th March 2017 travelled west from the active vent. This was followed by tephra fall on the 21st March 2018 that travelled south from the active vent and finally tephra fall during 9-11th April that travelled north-east from the active vent. The pyroclastic cone centred around the active vent had grown enough to split Lake Vui into two separate bodies. The influx of volcanic aerosols, gases and tephra turned the usually blue Lake Vui into a cloudy brown and red colour and Lake Manaro Ngoru had almost completely dried up (Figure E.2). Phase 3 of the eruption period coincided with Vanuatu's wet season. Tropical rainfall combined with thick unconsolidated tephra fall deposits increased the presence of lahars and mud flows within the numerous channels that drain water off Manaro Voui.

E.3.2 Volcanic hazard impact of Phase 3

Tephra fall and acid rain hazards continued to damage crops and contaminate drinking water sources, but with the larger eruption events, the impacts were more severe than those previously experienced in the earlier two phases. The area of barren vegetation at the summit of Manaro Voui had grown substantially (Figure E.2) and smaller crops exposed to thick tephra fall were being completely buried in some areas. Trees loaded with tephra were falling under the weight of the tephra and in some cases fell across roads, restricting access around the island. Lahars and mudflows also caused disruption to accessibility around the island by blocking roads and making crossings impassable by vehicle. Buildings exposed to the thick tephra fall sustained damage from tephra loading. Damage to buildings ranged from no damage, minor damage and complete collapse. By April flights into Longana airport in East Ambae were cancelled.

Figure E.2 The summit of Manaro Voui during a VMGD observation flight on the 21/04/2018 note the pyroclastic cone had grown and split Lake Vui into two separate water bodies, Lake Manaro Ngoru nearly completely dried up and the extent of vegetation damage at the summit (Photo source VMGD).

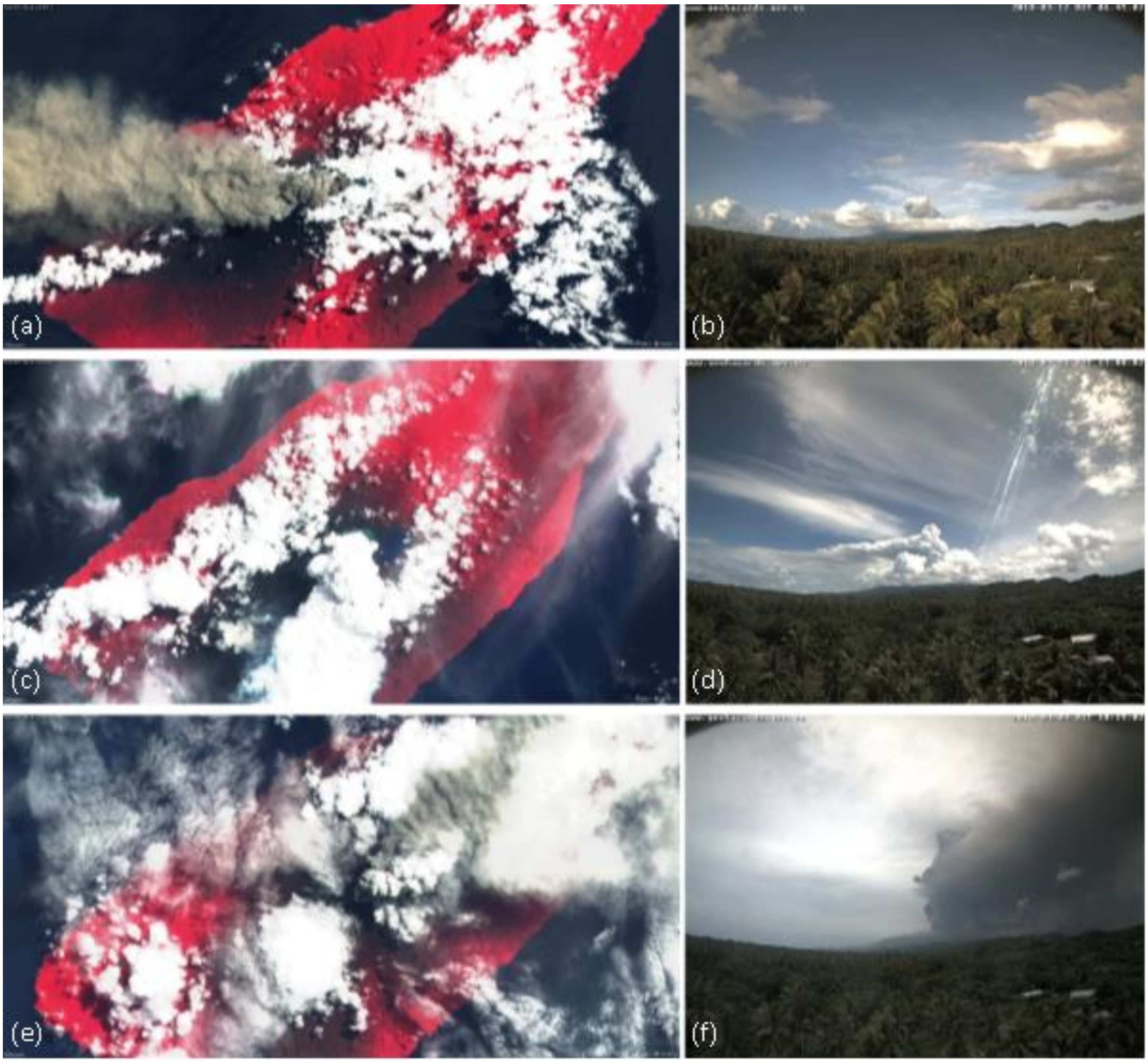

Figure E.3 Series of photos showing the range of activity from Manaro Voui during phase 3 of its eruption period. (a) Sentinel-2 False colour imagery of the 15/03/2018 eruption (b) webcam image of a tephra plume from an eruption on 12/03/2018 (Photo source VMGD) (c) Sentinel-2 False colour imagery of the 25/03/2018 eruption (d) webcam image of a tephra plume from the eruption on 25/03/2018 (Photo source VMGD) (e) Sentinel-2 False colour imagery of the 09/04/2018 eruption (f) webcam image of a tephra plume from the eruption on 09/04/2018 (Photo source VMGD).

E.3.3 Emergency response to Phase 3

Early in March 2017 VMGD, supported by GNS Science New Zealand and Massey University environmental scientists collected water and ash samples from across Ambae for analysis to provide information on the impact the eruption had on water quality and may have on people. On the 19th March 2018 VMGD upgraded Manaro Voui's VAL from 2 to 3, indicating Manaro Voui was in a state of minor eruption. During this time VMGD continued to monitor Manaro Voui's activity and provide information on the state of the volcano to the public. On Ambae, Penama's EOC were distributing rations to effected villages and managing evacuation centres. Vanuatu's NDMO were compiling assessments and developing a response plan as well as shipping relief supplies and personnel to register Ambae's displaced population (NDMO 2018, April 11). Some members of villages impacted by thick tephra falls had already self-evacuated to evacuation centres, but eventually evacuation was enforced from areas worst effected south and west of the active vent.

On the 13th April 2018 a state of emergency was declared by the Vanuatu Government's Council of Ministers for three months to allow for planning of both on-island and off-island evacuations (NDMO 2018, March 20). The Penama Provincial Government had identified potential on-island relocation sites for people displaced by the eruption, but with the state of emergency work went into identifying potential off-island relocation sites for the displaced population. VMGD continued to closely monitor Manaro Voui which at times was supported by GNS Science New Zealand scientists. NDMO continued assess the needs of displaced populations and distribute supplies to those impacted by the eruption.

The third phase ended mid-April when the eruptive activity from Manaro Voui ceased, but during May the Vanuatu Government continued to plan an off-island evacuation (NDMO 2018, May 04). By the end of May the plan for an off-island evacuation became voluntary, where those families who wished to relocate to areas identified as suitable on Maewo were provided full evacuation support from the Vanuatu Government to do so. On the 7th June 2018 VMGD lowered Manaro Voui's VAL level from 3 to 2 indicating that Manaro Voui was in a state of major unrest (VMGD 2018a).

E.4 Phase 4: July - November 2018

E.4.1 Volcanic processes in Phase 4

Phase 4 is characterised by a series of large eruptions and substantial degassing events (Figure E.4). During July 2018 alone Manaro Voui injected approximately 400,000 tons of SO_2 into the upper troposphere and stratosphere with the volcano having only released a further 200,000 tons of SO_2 for the rest of 2018 (NASA Earth Observatory 2018). The gas plume released on the 27th July 2018 was large enough that that gases and aerosols were picked up by satellites travelling over neighbouring Fiji more than 1,000 km away. There were two eruptions in particular that produced thick tephra fall deposits resulting in damage to some exposed buildings. The first was on the 1st July 2018 and travelled west from the active vent. The second was during the 16-25th July 2018 and travelled east-southeast from the active vent.

The eruptions during phase 4 coincided with Vanuatu's dry season so it was expected that most tephra plumes would travel west, down-wind from the dominant easterly trade winds like the eruption on the 1st July. However there was enough energy in the 2nd eruption that the tephra plume got up above the trade winds (~10 km) where the prevailing winds travel in the opposite direction towards the east. The second eruption was as large enough that tephra was deposited on neighbouring islands of Maewo and Pentecost over 30 km away and that in East Ambae sunlight was completely blocked, plummeting the day into darkness.

Despite phase 4 primarily occurring during Vanuatu's dry season, lahars and mud flows remained a hazard, particularly on the east where the easterly trade winds bring rain. By August the pyroclastic cone within Lake Vui covered much of the lake area and Lake Manaro Ngoru had completely dried up (Figure E.5).

E.4.2 Volcanic hazard impact of Phase 4

Tephra fall and acid rain hazards continued to damage crops, contaminate drinking water sources and cause further building damage. In some areas tephra fall was thick enough to collapse the tops of poly water tanks. In the east, crops were completely buried beneath tephra and coconut trees were collecting enough tephra in their leaves that the weight was causing the head of the tree to snap off. Because large areas of vegetation were covered in tephra vegetation available for livestock to forage was limited and where tephra was its thickest, some livestock died from malnutrition due to the lack of food and water. Lahars and mudflows continued to be an issue causing roadblocks and making some crossings impassable by vehicle. By the 27th July all primary schools on Ambae had closed as people were evacuated off the island.

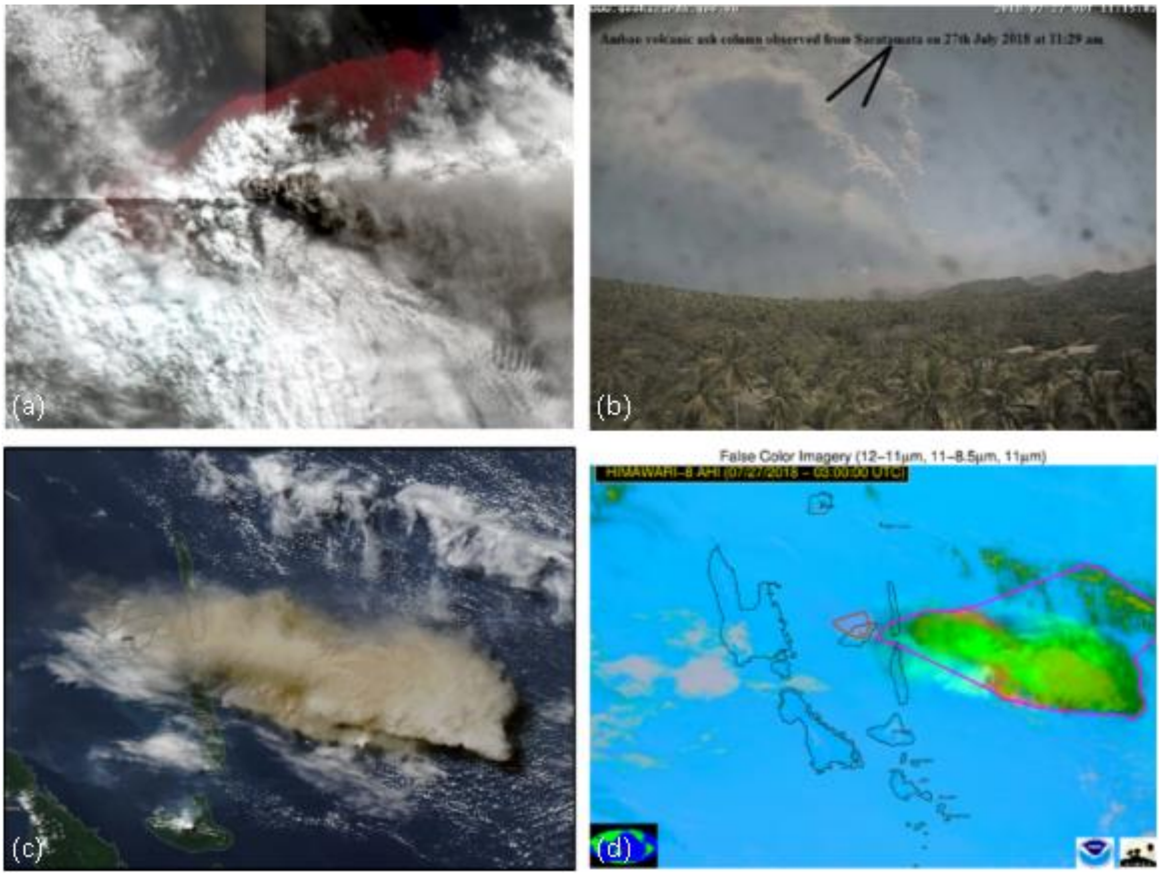

Figure E.4 Figure E.4 Series of photos showing the range of activity from Manaro Voui during phase 4 of its eruption period. (a) Sentinel-2 False colour imagery of the 23/07/2018 tephra plume (b) VMGD webcam image of the tephra plume from the 27/08/2018 eruption (photo source VMGD) (c) MODIS Corrected Reflectance Imagery of the tephra plume from the 27/08/2018 eruption Retrieved from NASA Worldview, 2018 (d) HIMAWARI-8 AHI satellite imagery of the SO_2 plume emitted from Manaro Voui on 27/07/2018 Retrieved from NOAA/CIMSS Volcanic Cloud Monitoring (2018).

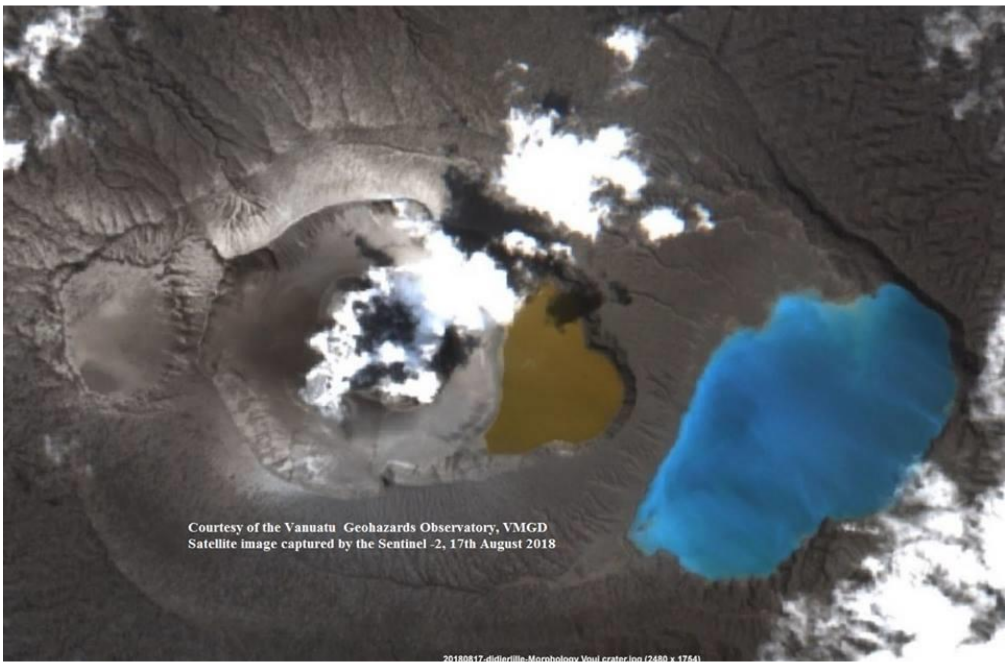

Figure E.5 Satellite imagery of the Manaro Voui summit on 17/08/2018 showing 1) the extent the pyroclastic cone had grown and filled Lake Vui 2) that Lake Manaro Ngoru had completely dried up (photo source VMGD)

E.4.3 Emergency response to Phase 4

On the 21st July 2018 VMGD upgraded Manaro Voui's VAL level from 2 to 3, indicating that the volcano was in a state of minor eruption (VMGD 2018b). The state of emergency that was issued on the 13th April 2018 had lapsed but the decision was made to extend the state of emergency to the 26th September 2018 (NDMO 2018, Sept 21). The initial response from NDMO and Penama's EOC was to evacuate those impacted from the large eruption during the 16-27th July to evacuation centres set up in areas not yet exposed to thick tephra fall. On the 26th of July 2018 the Vanuatu Governments Council of Ministers made the decision that a whole-island evacuation would be compulsory (NDMO 2018, Aug 6). The whole island evacuation plan was that the Vanuatu Government would support the evacuation of families to both Maewo and Espiritu Santo, but only those evacuated to Maewo would receive further support in the form of land, shelter, food, water and basic supplies. The whole-island evacuation was completed by the 13th August 2018.

During the time of the evacuation a team of people from New Zealand and Singapore under New Zealand's Ministry of Foreign Affairs and Trade Aid Programme supported VMGD on a Field survey on Ambae, Maewo and Pentecost (NDMO 2018, Aug 13). The team carried out ash and drinking water sampling, air quality monitoring and upgraded portable seismographs as well as continued to raise public awareness on the volcano and provide 4 EOC briefings, 2 in Saratamata (Ambae) and 2 in Maewo (NDMO 2018, Aug 13).

On the 28th August 2018 the Council of Ministers approved that the Government and humanitarian partners could provide food and relief items to those who decided to evacuate to Santo (NDMO 2018, Aug 31). On the 21st September the Council of Ministers decided to extend the state of emergency until the 26th November 2018. This ensured the continued capability to support relocated families and manage the ongoing response to Manaro Voui's eruption period and also meant that people could not return to Ambae until the state of emergency had ended.

NDMO continued to provide support and resources to families relocated to Maewo while the families established their 'second homes'. On the 21st September 2018 VMGD lowered Manaro Voui's VAL from 3 to 2 indicating that Manaro Voui was no longer in a minor state of eruption and was now in a state on major unrest (VMGD 2018c). Once the State of emergency ended residents were able to return to Ambae, but restricted resources meant the ability for residents to return and begin rebuilding was limited. For families that did return, many food crops had been destroyed either by volcanic hazards or livestock. Since people returned to Ambae the Council of Ministers decided that basic services such as education needed to be restored on Ambae and that a National Recovery Agency would be responsible for planning the recovery of Ambae (NDMO 2019).

Appendix F. Electronic appendix

- Excel spreadsheet of building inventory
- GIS files of tephra fall hazard models (March/April and July 2018)
- GIS files of surveyed building locations